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Low-Cost
Solar Array Project

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Progress Report 18

for the Period February to July 1981

and Proceedings of the 18th Project Integration Meeting

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by

Jet Propulsion Laboratory
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The JPL Low-Cost Solar Array Project is sponsored by the Department of Energy (DOE) and forms part of the Photovoltaic Energy Systems Program to initiate a major effort toward the development of low-cost solar arrays.

ABSTRACT

This report describes progress made by the Low-Cost Solar Array Project during the period February to July 1981. It includes reports on project analysis and integration; technology development in silicon material, large-area silicon sheet and encapsulation; process development; engineering, and operations. It includes a report on, and copies of visual presentations made at, the Project Integration Meeting held at Pasadena, California, on July 15 and 16, 1981.

CONTENTS

PROGRESS REPORT

Tables

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PROCEEDINGS

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NOMENCLATURE

A	Ampere(s)
Å	Angstrom(s)
ACM	Atmospheric corrosion monitors
AM	Air Mass (e.g., AM1 = unit air mass)
AR	Antireflective
BOS	Balance of System (non-array elements of a PV system)
CVD	Chemical vapor deposition
Cz	Czochralski (classical silicon crystal growth method)
DCS	Dichlorosilane
DLTS	Deep-level transient spectroscopy
DMP	2,4-dimethyl pentane
DOE	Department of Energy
EBIC	Electron-beam induced current
EFG	Edge-defined film-fed growth (silicon ribbon growth method)
EMA	Ethylene methylacrylate
EPDM	Ethylene-propylene-diene monomer
EPR	Ethylene propylene rubber
EPSDU	Experimental process system development unit
ESB	Electrostatic bonding
ESGU	Experimental sheet growth unit
EVA	Ethylene vinyl acetate
FAST	Fixed-abrasive slicing technique
FBR	Fluidized-bed reactor
GC	Gas chromatography
HCl	Hydrochloric acid
HEM	Heat exchanger method (silicon-crystal ingot-growth method)

HTSA	Hydrothermal stress analysis
ID	Inner diameter
ILC	Intermediate-load center
IPEG	Interim Price Estimation Guidelines
IPEG4	Improved Price Estimation Guidelines
I_{sc}	Short-circuit current
I-V	Current-voltage
LAPSS	Large-area pulsed solar simulator
LASS	Large-Area Silicon Sheet Task
LeRC	Lewis Research Center
LSA	Low-Cost Solar Array
mgSi	Metallurgical-grade silicon
MIT-LL	Massachusetts Institute of Technology Lincoln Laboratory
MBS	Multiblade sawing
MEPSDU	Module experimental process system development unit
NASA	National Aeronautics and Space Administration
NDE	Nondestructive evaluation
NOCT	Nominal operating cell temperature
NTCR	Near-Term Cost Reduction
O&M	Operation and maintenance
P	Individual module output power
PA&I	Project Analysis and Integration Area
P_{avg}	Module rated power at SOC, V_{no}
PDU	Process Development Unit
PEBA	Pulsed electron beam annealing
P/FR	Problem-failure report
PIM	Project Integration Meeting

P_{max}	Maximum power
PMMA	Polymethyl methacrylate
PnBA	Poly-n-butyl acrylate
$POCl_3$	Phosphorus oxychloride
PP&E	Production Process and Equipment Area
PRDA	Program Research and Development Announcement
PV	Photovoltaic(s)
PVB	Polyvinyl butyral
R&D	Research and development
RES	Residential experiment station
RFP	Request for proposal
RTR	Ribbon-to-ribbon (silicon crystal growth method)
RTV	Room-temperature vulcanized
SAIPEG	Sensitivity analysis using IPEG
SAMICS	Solar Array Manufacturing Industry Costing Standards
SAMIS	Standard Assembly-Line Manufacturing Industry Simulation
SEM	Scanning electron microscope
SEMI	Semiconductor Equipment Manufacturers Institute
SERI	Solar Energy Research Institute
$SiCl_4$	Silicon tetrachloride
SiF_4	Silicon tetrafluoride
$SiHCl_3$	Trichlorosilane
SOC	Silicon on ceramic (crystal growth method)
SOC	Standard operating conditions (module performance)
SOLMET	Solar radiation surface meteorological observations
TCS	Trichlorosilane
TEM	Transmission electron microscope

TR	Technical Readiness
UCP	Ubiquitous crystallization process
UV	Ultraviolet radiation
V_{no}	Nominal operating voltage
V_{oc}	Open-circuit voltage

PROGRESS REPORT

Project Summary

INTRODUCTION

This report describes the activities of the Low-Cost Solar Array Project from February to July, 1981, including the 18th LSA Project Integration Meeting (PIM) held July 15 and 16, 1981.

The LSA Project is assigned the responsibility for advancing solar array technology while encouraging industry to reduce the price of arrays to a level at which photovoltaic electric power systems will be competitive with more conventional power sources. Set forth here are the goals and plans by which the Project intends to accomplish this, and the progress that has been made during the period.

SUMMARY OF PROGRESS

Checkout of the Hemlock Semiconductor Corp. process development unit (PDU) for making silicon by a dichlorosilane process was completed and integrated operations of the PDU and an intermediate-sized silicon-deposition reactor were started.

Fabrication of equipment for the Union Carbide Corp. silane-to-silicon experimental process system development unit (EPSDU) was completed, but the start of mechanical and electrical installation was delayed because of FY81 budget recisions. The silicon shotter was assembled and initial tests with chunk silicon demonstrated that silicon shot formation was acceptable. The use of up to 21% silane in H_2 feedstock was successfully demonstrated in the FBR to give dense polysilicon deposition on seed particles.

Westinghouse Electric Corp. has successfully demonstrated and can routinely achieve constant width control for its silicon dendritic web crystal-growth process. Ribbons nearly 5 meters in length have been produced with width held uniform to within 0.1 mm.

Experiments at Mobil Tyco Solar Energy Corp. with their existing edge-defined film-fed growth ribbon growers are investigating design factors that limit growth speed and influence ribbon quality, for use in the design of a new four-ribbon (10-cm-wide) grower.

A Project-sponsored Wafering Workshop was held in Phoenix, Arizona. More than 80 persons attended; some 30 papers on wafering were presented. Empirical and theoretical experts exchanged information freely during exhaustive and comprehensive discussions.

All technical features for advanced wafering have been demonstrated individually. Future efforts will be directed toward combining these features into a practical wafering system.

PROJECT SUMMARY

The final 35-kg heat-exchange method (HEM) ingot required under the current contract with Crystal Systems, Inc., has been grown. The solidification time for the ingot was 40 h and the total cycle time was 70 h.

Based on Project activities in the identification and development of encapsulation material, Du Pont has indicated that the potential market for ethylene vinyl acetate (EVA) lamination film warrants their direct involvement. Du Pont has identified and worked with a custom extrusion vendor to develop a commercial source of rolls of standard EVA lamination film, 18 mils thick and up to 30 inches wide, that is non-blocking.

A preliminary draft copy of the Encapsulation Design and Material Specification Report for Industry Use was exhibited at the 18th Project Integration Meeting. The report was well received by the industrial participants at the conference.

An automated cell-stringing and soldering machine and an automated laminating system have been completed by Arco Solar, Inc., under a Project contract. Two hundred eighty eight modules were assembled using the automated equipment, 56 of which will undergo environmental testing at JPL.

Preliminary design reviews were held on the Westinghouse Electric Corp. and Solarex MEPSDU contracts. These contracts were revised to extend the period of performance in order to accommodate FY81 budget recisions.

Numerous reports covering module and array design technology were published. Subjects included standards for safety, module design and test specifications, low-cost structures for large ground mounted arrays, module and array circuit design optimization, module hot-spot durability design, fracture mechanics of silicon solar cells and module and array reliability.

Seven contractors were notified of their selection for negotiations in the Block V preliminary design procurement action. ARCO Solar, RCA Corp., Solar Power Corp. and Solarex were selected for their proposed designs of intermediate-load modules and General Electric Co., Mobil Tyco and Spire Corp. were selected for their residential module designs.

Area Reports

PROJECT ANALYSIS AND INTEGRATION AREA

INTRODUCTION

The objective of the Project Analysis and Integration (PA&I) Area is to support the planning, analysis, integration, and decision-making activities of the Project. This is done by developing and documenting Project plans, and by contributing to the generation and development of alternative Project plans through the assessment of technology options; by establishing standards for economic comparison of options under Project study and developing the analytical capabilities to perform the trade-offs required; by supporting the integration of the tasks within the Project and between the Project and other elements of the National Photovoltaics Program, and by providing coordinated assessment of, and progress toward achievement of, Project goals by the various areas of the Project working with the solar-array manufacturing industry and the National Photovoltaics Program.

PROGRESS

The metallization-grid-pattern optimization effort, in cooperation with the Process Development Area, is progressing. Two different designs have been metallized: the present conventional design, which is optimized using only two variables, and an improved design using four variables in the optimization. Results are being evaluated.

A revised power model, based on the series-parallel methodology developed by the Engineering Area, has been coded and initial test cases have been run. Model extensions, which include varying cell failure rates over time and replacing modules during system operation, are being incorporated.

Revisions and improvements in the SAMICS methodology are in progress. Release 4 of SAMIS (October 1) will have year-by-year financial reports. Revisions of Format C have been completed and are now available at stationery stores. A revised Format A will be ready for printing soon.

A first draft of an Engineer's Guide to SAMIS has been completed. The Guide is designed for the first-time or occasional user and contains explicit instructions for the use of SAMIS. Users of SAMIS will also benefit from a short course to be offered by JPL. A two-day course is planned to coincide with the 19th PIM.

A major effort to improve effluent control algorithms and to update control equipment and process costs has resulted in revision of the SAMICS Cost Catalog dealing with process waste disposal and pollution control. The revisions were based on input from process designers on control levels and methods now applicable or expected soon, and on cost input from control-equipment suppliers. Improvements in the approach to estimating environmental effluent costs were described at the 18th PIM and are contained in the PA&I Technology Session portion of the Proceedings.

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TECHNOLOGY DEVELOPMENT AREA

Silicon Material Task

INTRODUCTION

The objective of the Silicon Material Task is to establish the practicality of processes capable of producing silicon (Si) in a form suitable for use in the manufacture of terrestrial solar cells, at a price less than $14/kg (1980 $) by 1986. The program formulated to meet this objective provides for development of processes for producing either semiconductor-grade Si or a less pure, but utilizable (i.e., a solar-cell-grade) Si material.

TECHNICAL GOALS, ORGANIZATION AND COORDINATION

Solar cells are now fabricated from semiconductor-grade Si, which has a market price of about $65/kg. A drastic reduction in cost of material is necessary to meet the technology feasibility objectives of the LSA Project. Efforts are now under way to develop processes that will meet the Task objective in producing semiconductor-grade Si. Another means of meeting this requirement is to devise a process for producing a less-pure, so-called solar-cell-grade Si material. The allowance for the cost of Si material in the over-all economics of the solar arrays for LSA is dependent on optimization trade-offs, which concomitantly treat the price of Si material and the effects of material properties on the performance of solar cells. Accordingly, the program of the Silicon Material Task is structured to provide information for these tradeoffs concurrently with the development of high-volume, low-cost processes for producing Si. This structure has been described in detail in previous LSA Progress Reports. The program also includes economic analyses of silicon-producing processes and supporting efforts, both contracted and in-house at JPL, to respond to problem-solving needs.

Thirteen contracts in progress are listed in Table 1.

Table 1. Silicon Material Task Contractors

Contractor	Technology Area
Semiconductor-grade Silicon Processes	
Battelle Columbus Laboratories Columbus, Ohio JPL Contract No. 954339	Reduction of $SiCl_4$ by Zn in fluidized-bed reactor
Energy Materials Corp. Harvard, Massachusetts JPL Contract No. 955269	Gaseous-melt replenishment system

Table 1. Silicon Material Task Contractors (continued)

Hemlock Semiconductor Corp. Hemlock, Michigan JPL Contract No. 955533	Dichlorosilane CVD process
Union Carbide Corp. Tonawanda, New York JPL Contract No. 954344	Silane-Si process
Solar-Cell-Grade Silicon Processes	
SRI International Menlo Park, California JPL Contract No. 954771	Na reduction of SiF_4
Westinghouse Electric Corp. Trafford, Pennsylvania JPL Contract No. 954589	Reduction of $SiCl_4$ by Na in arc heater reactor
Impurity Studies	
Sah, C. T., Associates Urbana, Illinois JPL Contract No. 954685	Effects of impurities on solar cell performance
Westinghouse R&D Center Pittsburgh, Pennsylvania JPL Contract No. 954331	Definition of purity requirements
Supporting Studies	
AeroChem Research Laboratories Princeton, New Jersey JPL Contract No. 955491	Formation and growth of Si particles from SiH_4 at high temperatures
Lamar University Beaumont, Texas JPL Contract No. 954343	Technology and economic analyses
Massachusetts Institute of Technology Cambridge, Massachusetts JPL Contract No. 955382	Hydrochlorination of metallurgical-grade silicon and $SiCl_4$
Solarelectronics, Inc. Bellingham, Massachusetts JPL Contract No. 956061	Continuation of MIT effort on hydrochlorination of mgSi and $SiCl_4$
Texas Research and Engineering Institute Groves, Texas JPL Contract No. 956045	Continuation of Lamar's effort on technology and economic analyses

SILICON MATERIAL TASK

SUMMARY OF PROGRESS

Development of Processes for Producing Semiconductor-Grade Silicon

Four contracts in this category were active. Battelle Columbus Laboratories completed the draft of the final report on investigating the production of Si by the zinc reduction of silicon tetrachloride; the report will be released soon.

Energy Materials Corp. completed the draft of its final report on an Si melt-replenishment system for Czochralski crystal growth using trichlorosilane ($SiHCl_3$), under a near-term cost-reduction contract, and this report also will be released soon.

Hemlock Semiconductor Corp. is developing a process for making Si from dichlorosilane (SiH_2Cl_2) using Siemens-type deposition reactors. A one-year extension of the contract was executed in late June. A system for feeding cylinder-supplied SiH_2Cl_2 to reactors was constructed, and an intermediate-scale deposition reactor, modified for use with SiH_2Cl_2, was successfully tested with this reactant. The data indicate that the Si deposition rate is about double that obtained with the conventional reactant, $SiHCl_3$, an increase that is consistent with the rate increase required to meet program objectives.

Construction of the process development unit (PDU) for investigating the rearrangement of $SiHCl_3$ to SiH_2Cl_2 was completed, the PDU was integrated with the intermediate-scale reactor, and testing was begun. Operations proceeded very smoothly; 17 tests were completed by the end of June. Two problems have surfaced: the amount of Si being deposited on the bell jar walls, about 2% of the total amount being deposited, is excessive, and the power consumption of the deposition reactor is higher than desired.

Process flow diagrams for a 1000-MT/yr plant using the Hemlock process were updated, including safety-related changes that were made in the PDU design as a result of previous testing conducted as part of this program, such as elimination of SiH_2Cl_2 storage and dilution of the SiH_2Cl_2 immediately as it leaves the distillation column on its way to the deposition reactor.

Union Carbide Corp. continued construction of the 100-MT-Si/yr experimental process system development unit (EPSDU) at East Chicago, Indiana. All civil and structural work was completed. Most of the equipment has been delivered to the site, and most major equipment pieces have been inspected and placed in position.

Bids for the mechanical installation were received from five bidders, and these responses are being evaluated. The electrical-installation bid package is being prepared. Awarding of these installation subcontracts will probably be delayed because of an FY81 funding recision.

In the UCC R&D program, the Si powder melter subcontract work at Kayex continued, with assembly of the shotter and completion of several tests in which Si chunk material was melted and converted to product containing some free-flowing shot.

The fluidized-bed silane (SiH_4)-pyrolysis PDU was assembled and operated successfully with SiH_4 feed concentrations ranging from 10% to 21%.

Particle morphology appears to be excellent, and little undesirable Si powder was produced. The effort was stopped in mid-May because of budget contraints.

Development of Processes for Producing Solar-Cell-Grade Silicon

Final reports were issued by SRI International on the process for producing Si by the sodium reduction of silicon tetrafluoride, and by Westinghouse Electric Corp. on the arc-heater process, in which silicon tetrachloride is reduced by sodium.

Impurity Studies

C. T. Sah Associates is developing a computer model based on the fundamental parameters of solar cells and applying it to the determination of the effects of impurities and defects of Si on solar cell performance. The effect of cell thickness on the performance of Si cells containing impurity recombination centers was analyzed using a transmission-line-circuit model and zinc (Zn) impurity as the model recombination center. Results show that the AM1 efficiency has a broad maximum (less than 0.1% variation from 20 to 70 μm) in back-surface-field $n^+/p/p^+$ and $p^+/n/n^+$ cells of 17% efficiency with 5×10^{14} atoms/cm^3 base doping and 10^{12} atoms Zn/cm^3. Back-surface reflection in cells of optimum thicknesses increases the efficiency by less than 1% through increase of J_{sc}.

Comparison of the theory with measurements on impurity-containing thin cells made on web using Zn-vapor-reduced silicon was attempted. The base resistivity is about 0.3 ohm-cm or 6×10^{16} holes/cm^3. The cells have large excess dark current that varies as exp (qV/1.63kT) up to and including V_{oc} and is independent of cell area (one mm^2 to one cm^2). Uniform Zn concentration theory predicts the normal current behavior, exp (qV/kT). Capacitance-voltage measurements suggest that there is a boundary that may account for the large excess current due to recombination in the space charge layer.

In the program by Westinghouse R&D Center to determine the effects of impurities on the performance of solar cells, the Phase IV program has been completed and a final report is being prepared. The effort included: evaluation of experimental Si materials, investigation of impurity effects in polycrystalline devices, identification of impurity thresholds for high-efficiency cells, assessment of process effects such as ion implanting on impurity-doped devices, and an extension of studies to identify long-term impurity effects. Some of the major results during this period follow:

The threshold impurity concentration for breakdown of a smooth crystal-liquid interface, C_ℓ^*, is 2 to 10 times smaller for polycrystalline than for single-crystal ingots.

Using a model relating the measured value of C_ℓ^* to experimental growth parameters, the values of the liquid impurity diffusion constants were calculated for gadolinium, zirconium, molybdenum, tungsten, vanadium, titanium, iron, cobalt, palladium, silver, and copper in Si. The parameter D_ℓ ranged from 1.5 to 4.2×10^{-4} cm^2/sec for these elements; the values are similar to those reported for other metals in liquid Si.

Of the various gettering treatments investigated, the most effective for titanium appears to be high-temperature reaction in hydrogen chloride (HCl) alone or phosphorus oxychloride ($POCl_3$) alone. For copper-doped cells, none of the gettering treatments (implant damage plus HCl or $POCl_3$ implant damage plus heat treatment, or HCl/$POCl_3$ alone) raises cell efficiency to that of the baseline devices.

Extensions of the experimentally supported impurity performance model to high-efficiency devices indicate that impurity tolerance is less in high-efficiency than conventional n^+p devices and that this impurity sensitivity can be reduced by using thinner high-efficiency cells.

Supporting Studies

AeroChem Research Laboratories completed its experimental program in the investigation of the formation and growth of Si particles from the decomposition of silane (SiH_4) at high temperatures. Experiments on the SiH_4-to-particle formation process were conducted, in which the extent of SiH_4 decomposition, particle size, particle concentration, and particle growth rate were measured as functions of residence time, temperature, pressure, and SiH_4 concentration. Experiments were also made with particle seeding. The final report on the program was prepared and issued.

The report by Lamar University on its process feasibility study, covering all efforts since contract inception in 1975, was issued. The contract follow-on was initiated; it will be conducted by the Texas Research and Engineering Institute with the same principal investigator, C. Yaws, who was in charge of the effort at Lamar. The initial work will be a chemical-engineering analysis of the Hemlock Semiconductor Corp. process for producing Si from SiH_2Cl_2.

The Massachusetts Institute of Technology (MIT) completed a two-year contract to investigate the hydrochlorination of metallurgical-grade Si and $SiCl_4$ to form $SiHCl_3$, in support of the Union Carbide program. Experiments indicated that the fines that are elutriated from the reactor during operation contain a high proportion of the metallic impurities in metallurgical-grade Si. Fines elutriation can therefore be employed as part of the purification process. Experiments also showed that in the presence of cuprous chloride catalyst, the silicon mass in the fluidized bed reactor has a long reaction life under the expected conditions of operation. The final report on the contract was issued.

The follow-on contract to the MIT work was initiated. The effort will be conducted at Solarelectronics under the same principal investigator who directed the MIT program, J. Mui.

The JPL in-house program included effort on the fluidized-bed reactor (FBR), conversion of SiH_4 to molten Si, and impurity investigations.

The design of a 6-in.-dia FBR for the investigation of SiH_4 pyrolysis was completed, and fabrication was started. Experiments in a 2-in.-dia FBR at high SiH_4 concentration, including 100% SiH_4, were conducted successfully without bed agglomeration and with less than 10% fines. These results are significant in that they may aid considerably in achieving lower silicon costs by means of increased throughput, since FBR operation with 10 mole % SiH_4 in hydrogen has

already been shown analytically to be economically attractive. The Si deposits were dense and coherent.

The silane-to-molten-silicon (SMS) converter offers the potential of a one-stage conversion process. The unit was modified to allow rapid experimentation at high temperatures (1500 to 1750°C). Preliminary short-duration experiments were then conducted to examine the effects of configuration, flow, and temperature on the conversion of SiH_4 to molten Si. Two problems have been encountered: plugging of the SiH_4 injector by Si that rapidly forms as the SiH_4 is introduced into the hot reactor, and formation of Si powder that is swept out of the reactor without melting. The experiments are providing information for design changes to circumvent these problems.

In the analysis of electrically active impurities using thermally stimulated capacitance (TSCAP) measurements, an evaluation indicated that very consistent equipment operation was required to obtain the necessary measurement accuracy. As a result, the TSCAP system was automated by use of a calculator-controlled system. The system measures three parameters: characteristic temperature of a trap, trap concentration, and trap energy level. Initial tests were made on a sample containing gold. The results indicate that small errors in measuring temperature may be causing errors in trap energy level. Improvements are being made to eliminate this source of error.

A Zeeman atomic absorption spectrometer to be used for impurity analysis was procured and put into operation. The spectrometer uses the Zeeman effect on a resonant transition to correct automatically for background interference, making it possible to measure the concentrations of trace elements in a host material directly without chemical pretreatment. Sensitivity is in parts-per-billion for elements such as iron, copper, chromium, and manganese. Elements that form carbides, such as boron, or those that are extremely refractory, such as tungsten, are difficult to measure. The instrument is being calibrated.

In the effort on consolidation of sub-μm Si powder, the powder compactor-extruder, which feeds the material to the melter, was modified and successfully operated.

Large-Area Silicon Sheet Task

Present solar-cell technology is based on the use of silicon wafers obtained by slicing Czochralski (Cz) or float-zone ingots (up to 10 cm in diameter), using single-blade inner-diameter (ID) diamond saws. This method of obtaining single-crystal silicon wafers is tailored to the needs of large-volume semiconductor device production (e.g., integrated circuits, discrete power and control devices other than solar cells). The small market offered by present solar-cell users does not justify industry's development of the high-volume silicon production techniques that would result in low-cost photovoltaic electrical energy.

The improvement of the standard Czochralski ingot growth process by reduction of expendable material costs and improvement of ingot growth rate together with improved slicing techniques will produce large areas of silicon at costs meeting the goals of the LSA Project. Growth of large ingots by casting techniques, such as the heat exchanger method (HEM) growth, and the ubiquitous crystallization process (UCP) can reduce sheet costs further.

The objective of the Large-Area Silicon Sheet Task is to develop and demonstrate the feasibility of several processes for producing large areas of silicon-sheet material suitable for low-cost, high-efficiency solar photovoltaic energy conversion. To meet the objective of the LSA Project, sufficient research and development must be performed on a number of processes to determine the capability of each of producing large areas of crystallized silicon at a low cost. The final sheet-growth configurations must be suitable for direct incorporation into an automated solar-array processing scheme.

Growth of crystalline silicon material in a geometry that does not require cutting to achieve proper thickness is an obvious way to eliminate costly processing and material waste. Growth techniques such as edge-defined film-fed growth (EFG) and dendritic growth (web), are possible candidates for the growing of solar-cell material.

Research and development of ribbon and ingot growth, and of multiple-blade, multiple-wire, and inner-diameter (ID) blade cutting, initiated in 1975-76, are in progress.

ORGANIZATION AND COORDINATION

When the LSA Project was initiated (January 1975) a number of methods potentially suitable for growing silicon crystals for solar-cell manufacture were known. Some of these were under development; others existed only in concept. Development work on the most promising methods is continuing. After a period of accelerated development, these methods will be evaluated and the best will be selected for advanced development. As the growth methods are refined, integrated process schemes will be developed by which the most cost- effective solar cells can be manufactured.

The Large-Area Silicon Sheet Task effort is organized into four phases: research and development of sheet growth methods (1975-77); advanced development of selected growth methods (1977-80); prototype development (1981-82); development, fabrication, and operation of pilot production growth plants (1983-86).

Large-Area Silicon Sheet Contracts

Research and development contracts awarded for growing crystalline silicon material for solar cell production are listed below. Preferred growth methods for further development have been selected.

Table 2. Large-Area Silicon Sheet Task Contractors

Contractor	Technology Area
Ingot Technology	
Crystal Systems, Inc. Salem, Massachusetts JPL Contract No. 954373	Heat exchanger method (HEM) ingot growth; fixed-abrasive slicing technique (FAST)
Kayex Corp. Rochester, New York JPL Contract No. 955733	Advanced Cz growth (Adv. Cz)
P.R. Hoffman Co. Carlisle, Pennsylvania JPL Contract No. 955563	Multiblade slurry slicing technique (MBS)
Silicon Technology Corp. Oakland, New Jersey JPL Contract No. 955131	Internal diameter (ID) slicing
Semix Inc. Gaithersburg, Maryland DOE Contract No. DE-F101-80ET 23197	Ubiquitous crystallization process (UCP)
Shaped Sheet Technology	
Mobil Tyco Solar Energy Corp. Waltham, Massachusetts JPL Contract No. 954355	Edge-defined film-fed growth (EFG)
Westinghouse Electric Corp. Pittsburgh, Pennsylvania JPL Contract No. 955843	Dendritic web growth (web)

Large-Area Silicon Sheet Task

Present solar-cell technology is based on the use of silicon wafers obtained by slicing Czochralski (Cz) or float-zone ingots (up to 10 cm in diameter), using single-blade inner-diameter (ID) diamond saws. This method of obtaining single-crystal silicon wafers is tailored to the needs of large-volume semiconductor device production (e.g., integrated circuits, discrete power and control devices other than solar cells). The small market offered by present solar-cell users does not justify industry's development of the high-volume silicon production techniques that would result in low-cost photovoltaic electrical energy.

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Table 2. Large-Area Silicon Sheet Task Contractors (Continued)

Material Evaluation	
Applied Solar Energy Corp. City of Industry, California JPL Contract No. 955089	Cell fabrication and evaluation
Cornell University Ithaca, New York JPL Contract No. 954852	Characterization - Si properties
Materials Research, Inc. Centerville, Utah JPL Contract No. 957977	Quantitative analysis of defects and impurity evaluation technique

INGOT TECHNOLOGY

Crystal Systems, Inc.: The Schmid-Viechnicki technique (heat-exchanger method or HEM) was developed to grow large single-crystal sapphire. Heat is removed from the crystal by means of a high-temperature heat exchanger. The heat removal is controlled by the flow of helium gas (the cooling medium) through the heat exchanger. This obviates motion of the crystal, crucible, or heat zone. In essence, this method involves directional solidification from the melt where the temperature gradient in the solid is controlled by the heat exchanger and the gradient in the liquid is controlled by the furnace temperature. The overall goal of this program is to determine whether the heat-exchanger ingot casting method can be applied to the growth of large shaped-silicon crystals of 30-cm-cube dimensions of a quality suitable for the fabrication of solar cells. This goal is to be accomplished by the transfer of sapphire-growth technology (50-lb ingots have already been grown), and theoretical considerations of seeding, crystallization kinetics, fluid dynamics, and heat flow for silicon.

Kayex Corp.: In the advanced Cz contracts, efforts are geared to developing equipment and a process to achieve the cost goals and demonstrate the feasibility of continuous-Cz solar-grade crystal production. Kayex has already demonstrated the growth of 150 kg of single-crystal material, using only one crucible, by periodic melt replenishment.

Semix: The semicrystalline casting process is a Semix proprietary process yielding a polycrystalline silicon "brick" capable of being processed into cells of up to 16% efficiency at AM1.

Crystal Systems, Inc., P. R. Hoffman Co. and Silicon Technology Corp.: Today most silicon is sliced into wafers with an inner-diameter saw, one wafer at a time. Advanced efforts in this area are continuing. The multiwire slicing operation uses reciprocating blade-head motion with a workpiece fed from below. Multiwire slicing uses 5-mil steel wires surrounded by a 1.5-mil copper sheath that is impregnated with diamond as an abrasive.

The multiblade slurry technique is similar to the multiwire slicing technique, except that low-carbon steel blades (typically 1 cm in height and 6 to 8 mils thick) are used in conjunction with an abrasive slurry mixture of SiC and oil.

MATERIAL EVALUATION

Applied Solar Energy Corp. (ASEC): Proper assessment of potential low-cost silicon sheet materials requires the fabrication and testing of solar cells using reproducible and reliable processes and standardized measurement techniques. Wide variations exist, however, in the capability of sheet-growth organizations to fabricate and evaluate photovoltaic devices. It is therefore logical and essential that the various forms of low-cost silicon sheet be evaluated impartially in solar cell manufacturing environments with well-established techniques and standards. ASEC has been retained to meet this need.

Materials Research, Inc.: The current MRI sheet defect-structure assessment effort includes a correlation of impurity distributions with defect structures in various sheet materials obtained from the ingot and shaped-sheet manufacturers.

SHAPED-SHEET TECHNOLOGY

Mobil Tyco Solar Energy Corp.: The EFG technique is based on feeding molten silicon through a slotted die. In this technique, the shape of the ribbon is determined by the contact of molten silicon with the outer edge of the die. The die is constructed from material that is wetted by molten silicon (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG process to a speed of 4.5 cm/min and a width of 10.0 cm. In addition to the development of EFG machines and the growing of ribbons, the program includes economic and theoretical analysis of ribbon thermal and stress conditions.

Westinghouse: Dendritic web is a thin, wide ribbon form of single-crystal silicon produced directly from the silicon melt. "Dendritic" refers to the two wirelike dendrites on each side of the ribbon, and "web" refers to the silicon sheet that results from the freezing of the liquid film supported by the bounding dendrites. Dendritic web is particularly suited for fabrication into solar cells for a number of reasons, including the high efficiency of the cells in arrays and the cost-effective conversion of raw silicon into substrates.

Encapsulation Task

INTRODUCTION

The objective of the Encapsulation Task is to develop and qualify one or more solar-array module encapsulation systems that have demonstrated high reliabilities and 20-year lifetime expectancies in terrestrial environments, and that are compatible with the low-cost objectives of the Project.

The scope of the Encapsulation Task includes developing the total system required to protect the optically and electrically active elements of the array from the degrading effects of terrestrial environments. The most difficult technical problem has been the development of high-transparency materials for the sunlit side that also meet the LSA Project low-cost and 20-year-life objectives. In addition, technical problems have ocurred at interfaces between elements of the encapsulation system, between the encapsulation system and the active array elements, and at points where the encapsulation system is penetrated for external electrical connections.

The encapsulation system also serves other functions in addition to providing the essential environmental protection; e.g., structural integrity, electrical resistance to high voltage and dissipation of thermal energy. The approach used to achieve the objective of the Encapsulation Task includes an appropriate combination of contractor and JPL in-house efforts, which can be divided into two technical areas:

(1) Materials and Process Development. This effort includes all of the work necessary to develop, demonstrate, and qualify one or more encapsulation systems to meet the LSA Project cost and performance goals. It includes the testing of off-the-shelf materials, formulation and testing of new and modified materials, development of automated processes to handle these materials during fabrication of modules, and systems analysis and testing to develop optimal module designs.

(2) Life Prediction and Material Degradation. This work is directed toward the attainment of the LSA Project 20-year-minimum life requirement for modules in 1986. It includes the development of a life-prediction method applicable to terrestrial photovoltaic modules and validation by application of the method to specific photovoltaic demonstration sites. Material degradation studies are being conducted to determine failure modes and mechanisms. This effort supports both the materials and processes development work and the life-prediction method development.

SUMMARY OF PROGRESS

Materials and Process Development

Pottant Materials

New material products tailored to the specific requirements defined and publicized by the LSA Project for PV module encapsulation are now available from general suppliers. These products include nonblocking ethylene vinyl acetate (EVA) film in production quantities, laminated EVA-Tedlar sheets, and

polymethyl methacrylate (PMMA) UV-screening cover films from Du Pont and 3M. Springborn Laboratories, Inc., has also achieved pilot-plant production capability for poly-n-butyl acrylate (PnBA). PnBA and ethylene methylacrylate (EMA) casting syrups are available for industrial evaluation. Springborn is also evaluating other casting liquids, including an aliphatic polyether urethane from Development Associates.

In a survey of edge-seal and gasket materials, Springborn has identified ethylene-propylene-diene monomer (EPDM) as the lowest-cost gasketing material now available. This material, specifically Du Pont Nordel EPDM with a proprietary formulation designed for a long outdoor service life, has been purchased and is being evaluated.

Springborn is also evaluating low-soiling surfacing materials. Preliminary results in this area indicate that glass, Tedlar and acrylic front-cover films having surface treatments containing fluorine remain measurably cleaner than either untreated controls or materials having other anti-soiling surface treatments.

Hygroscopic expansion has been verified as a major cause of cell cracking in modules using woodboard substrates. Various methods of coating and sealing the substrate to prevent initial desiccation during vacuum-bag processing have not been successful. Materials and processing studies in this area are continuing at JPL and Springborn.

A report, "Photovoltaic Module Encapsulation Design and Materials Selection" (JPL Document No. 5101-177, in press), has been written to describe the module encapsulant material requirements for the various functional elements of a complete photovoltaic module encapsulation package. This information is presented in terms of material properties, performance, life and cost requirements. It describes the status and availability of potential material and process candidates with criteria and guidelines for their selection, processing, and optimizing configurations for specific applications. This report is expected to be published and distributed in about three months.

UV Absorbers

Work has continued on the development of chemically bound UV stabilizers for polymer films. O. Vogl's group at the University of Massachusetts has successfully grafted 5-vinyl tinuvin to a wide variety of polymers including EVA, PMMA, polycarbonate, nylon and PnBA. Evaluation of these modified polymers is being conducted at Springborn.

Development of other (more available) UV stabilizers by Vogl has resulted in the synthesis and copolymerization of 2(2-hydroxy-5-isopropenylphenyl) 2H-benzotriazole (2H5P). The compound does not homopolymerize, however, and grafting attempts with 2H5P have not been successful. At the same time, and based on the same intermediates as those used for the synthesis of 2H5P, a new synthesis of 2(2-hydroxy-5-vinylphenyl) 2H-benzotriazole (2H5V) has been carried out that promises to have advantages over 2H5P. Grafting of 2H5V onto a number of common polymers has been accomplished, including atactic polypropylene, polyethylene-co-vinyl acetate, PMMA, polybutyl acrylate and polycarbonate. In preliminary experiments 2H5P does not graft under similar conditions.

Efforts are continuing in the evaluation of the spectral characteristics of these compounds to establish clearly and beyond any doubt the most effective derivative of 2(2-hydroxyphenyl) 2H-benzotriazole as the prime candidate for polymerizable UV stabilizers for the LSA Project.

Springborn, with JPL, has begun the evaluation of new polymeric and monomeric UV stabilizers and high-performance anti-oxidants. These materials have just become available from American Cyanamid Co. for evaluation as long-life stabilization additives for low-cost encapsulation materials.

Electrostatic Bonding

All of the electrostatically bonded (ESB) minimodules have been received from Spire Corp. This includes five modules with preformed mesh interconnects. All modules are undergoing laboratory and field testing.

Antireflective (AR) Coatings

Both AR coating contracts with Motorola Inc. have been completed. All deliverables (reports and glass samples) have been received. Both AR coatings, acid etch and sodium silicate, have been deployed for outdoor evaluation by JPL.

Module Design

Experimental validation and updating of an optical-performance prediction model is continuing at Spectrolab, Inc. The effects of various module encapsulant design parameters on module thermal response, optical performance, electrical isolation, and solar cell stresses are being evaluated. It was observed that module electrical isolation approaching intrinsic material properties could be achieved with two or more dielectric layers (pottant plus film). Electrical breakdowns finally ocurred at sharp corners and edges of solar cell or circuit components. Voids and bubbles in the encapsulant did not significantly contribute to electrical breakdown. Optical evaluation of various module configurations verified the effectiveness of AR coatings, as compared with uncoated designs. It was also observed that power output was independent of EVA thickness for thicknesses between 10 and 35 mils. It was further found that designs employing Craneglas above solar cells were as efficient as, if not more efficient than, modules not having Craneglas above the cells.

A report has been completed on the thermomechanical modeling and optimal stress design of a Solarex minimodule. Results indicate that modules with substrates and adhesives having lower moduli of elasticity and thicker adhesive bond lines have lower maximum thermally induced stresses. Guidelines are presented for evaluating stress levels and adhesive thickness of future designs.

A joint effort between JPL and Spectrolab is under way to develop graphical design analysis curves, i.e., master curves with reduced variables. These curves, when defined and verified, will enable the module designer to optimize the encapsulant-system design parameters such as pottant thickness, pottant modulus, and cover-film properties and to assess which module performance characteristics are most affected by encapsulant configuration and material choices.

Based on these curves, Spectrolab will fabricate and test a 1.4-m-square module of a design having the most favorable life-cycle energy cost.

Illinois Tool Works (ITW) has demonstrated the capacity to produce operational solar cells having front and back metallization and antireflective coatings deposited by gasless ion plating. The process has repeatedly produced cells equal to or better than comparable commercial cells in performance, at a projected (SAMIS) production cost of 5.6¢/W_p for the metallization plus AR coating.

The problem of ohmic contact of the ion-plated metallization on the p back surface of Spectrolab wafers is continuing to be investigated at ITW.

Bonding and Primers

E. P. Plueddemann of Dow Corning Corp. is continuing his work on encapsulant primer systems. Functional EVA-to-glass and EVA-to-polyester film primers (independently developed) have been identified. These primers appear initially to work also for EMA, although testing is incomplete. Work on primers for bonding fluorocarbon films to EMA, EVA and PnBA is continuing. Progress is also being made on polyurethane coating pottant primers. Complete development of these is expected within a year.

Material Degradation and Life Prediction

Photodegradation Model for EVA

The general computer program necessary to simulate the process of photooxidation is now in routine use in the University of Toronto laboratory. The operational facility can generate concentration-time profiles of all of the identifiable species for a given input mechanism and rate data set. A summary of three tentative conclusions produced by computer simulation are: the major products of alkane photooxidation are isomeric alcohols, ketones and water; there is minimal crosslinking at low levels of oxidation in linear alkanes, and the product distribution and overall rate of oxidation is dominated by the fate of the peroxy radicals formed in the propagation cycle after proton abstraction from the alkane.

Experimental studies of photooxidation of n-decane and 2,4-dimethyl pentane (DMP) are being done to improve the initial mechanism proposed for the photooxidation of hydrocarbon segments of EVA. Most of the products of photooxidation of n-decane and DMP, such as isomeric alcohols and ketones, have been identifiable using gas chromatography (GC). Failure to observe speculated results, however, suggests that only primary products associated with the early stage of photooxidation are being formed under the photooxidation experimental setup (medium-pressure Hg lamp with a Pyrex glass UV-filtered vessel and irradiation times of 4 to 48 h). In extended outdoor exposure, slow secondary processes become significant and may even dominate final failure modes associated with embrittlement, permeability, discoloration, etc. If these processes can be identified in the early stage, retardation, monitoring or control of the photooxidative breakdown of these plastic materials may be possible. Further testing to quantify these processes is continuing.

The automatic viscometer capable of measuring up to 50 or 60 solutions in automatic sequence is now fully operational and has been demonstrated. The laser-GC photolysis apparatus which, by monitoring yields of carbon monoxide, acts as a probe of early photooxidation in polymer films, remains to be demonstrated.

Stress relaxation of EVA at small strains (<10%) is being measured at various temperatures by JPL. The objective of this work is to obtain an understanding of flow behavior and its dependence on photothermal degradation of EVA. The log stresses vs log time curves for data between -50°C and +30°C were found to be superimposable. This indicates that flow behavior of EVA may be similar to that of other elastomers, although X-ray diffraction has shown that EVA is a crystalline copolymer. Measurements at other temperatures are in progress. These data will be used in the development of master curves that are needed for life-prediction modeling.

Corrosion Diagnostics and Modeling

The 1980 Annual Report was received from the Rockwell Science Center. The major conclusions discussed in this report are summarized:

(1) Completion of a 13-month field study of atmospheric corrosion at the LSA test site at Mead, Nebraska, verifies the fundamental assumptions of a new atmospheric corrosion model, which predicts that corrosion rate is the product of the moisture condensation probability (P_c) and the maximum ionic diffusion current (I_L) at the corrosion interface. Encapsulant protection is specifically related to suppression of I_L at the corrosion interface.

(2) Alternating-current impedance measurements as a function of frequency combined with impedance spectrum analysis appears to provide a new and versatile nondestructive evaluation (NDE) for solar arrays.

(3) A computer model for hydrothermal stress analysis (HTSA) has successfully analyzed and predicted the internal stresses and solar-cell cracking mechanisms in LSA modules using a fiberboard substrate. Diffusion-barrier coatings of EVA or polytrifluoroethylene (KEL-F) delay but do not change the failure process.

The atmospheric corrosion model and corrosion monitors are now being combined in a new laboratory test plan for encapsulant bond evaluation. Both ionic conduction and electromechanical mechanisms of corrosion are being evaluated under laboratory simulation of atmospheric corrosion conditions. The Science Center atmospheric corrosion simulator, which controls UV, moisture, and temperature cycles, is being used in these studies.

Efforts are now concentrated on developing corrosion monitors as NDE tools for module-life prediction and on developing corrosion models and materials selection criteria for environmentaland corrosion-resistant interfaces. Integrated with the use of atmospheric corrosion monitors (ACM) for encapsulant primer evaluations, ac impedance measurements now provide information on modules undergoing moisture diffusion.

ENCAPSULATION TASK

Experiments aimed at correlating moisture diffusion and ac impedance responses of two Block IV modules show that the effect of small changes in moisture content can be sensed, despite scatter in the measurement resulting from thermal fluctuations. The thermal fluctuations have recently been eliminated through tighter thermostatic control. These baseline tests have been extended to include a study of the temperature response of one of the cells. In these tests the cell was thoroughly dried and stored in a desiccator. Ac impedance of the cell under zero bias and in a dark, thermostatted cabinet provided the shunt resistance (R_{SH}) of the cell as a function of temperature. A plot of $1/R_{SH}$ vs $1/T^{oK}$ was found to be linear. The activation energy resulting from this Arrhenius behavior is 7.23 kcal/mole (0.31 eV). The 7.23 kcal/mole activation energy for the dry cell corresponds to a charge transport other than that controlled by liquid state diffusion and may result from a process internal to the semiconductor.

The delivery of the field-instrument design for the measurement of ac impedance has been postponed until September. It is expected that the design will incorporate slight modifications in available hardware.

An inventory of materials used for module encapsulation has been supplied to the Science Center by JPL. Some of these materials will be screened for their corrosion-protection potential by means of the ACM technique.

Photodegradation of Polymers

Studies are continuing by C. Rogers's group at Case Western Reserve University on the photodegradation of PnBA. The studies use Fourier transform infrared (FTIR) absorbance and difference spectra to characterize changes in unmodified PnBA after weathering in the QUV Accelerated Weathering Tester. Results to date indicate that PnBA degrades by means of chemical crosslinking and chain scission in the presence of oxygen. It was also observed that unmodified PnBA is fairly stable in oxygen-free environments. This leads to a preliminary conclusion that, for PnBA, antioxidant additives may be more important to long-term stability than UV stabilizers.

Fracture and Crack Modeling

An evaluation of commercially available finite-element programs to calculate the crack-tip stress-intensity factors (K_{IC}) with temperature gradients has been completed. Several programs were identified including MARC (MARC Analysis Reseach Co.), ANSYS (Swanson Analysis Systems, Inc.), ADINA (MIT), and TEXGAP (University of Texas, Austin).

The TEXGAP program, a FORTRAN-coded finite-element computer program, was received by JPL. The main feature of the program, not available in other commercial programs, is the availability of a finite-element code that has been developed for the analysis of cracks in structures due to differential temperature loading. To date, the TEXGAP program has not been successfully run at JPL; additional programming and engineering effort would be required to prepare the program for use in test-case calculations. This will not be done; this contract has been terminated due to funding cutbacks. The results of the program were to have been used for solar-array life prediction.

Module Life Testing

Validation of the Battelle accelerated-test plan at JPL has been discontinued after 120 days (360 cycles) of accumulated test time. Electrical tests at room temperature continue to show that one module has completely failed, and four others exhibit power losses exceeding 10%. Visual inspection continues to show additional stress cracks in the interconnects, and small delaminations are beginning to appear. Electrical continuity tests at +95°C indicate that only one of the 10 modules is still functional at that temperature, and 50% of the modules exhibit open circuits at 60°C. Nearly all of the performance degradation appears to be attributable to interconnect fatigue failure. A final report on the study is being prepared.

Minimodule qualification testing (thermal cycling and humidity-freeze cycling) and measurement of nominal operating cell temperatures (NOCT) are about 50% complete. NOCT values have ranged from 39.8°C to 45.7°C for six module designs. All field-test minimodules have been deployed at the JPL and Goldstone weathering sites. The Point Vicente weathering site will be reactivated in August, when increased module security will be available.

Very little visual degradation of minimodule or two-cell subminimodule encapsulation has been detected, but a great number of cracked cells have been reported in modules with wood-fiber hardboard substrate. This is primarily due to the hygroscopic expansion of the substrate. Various attacks on this problem are being developed.

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PROCESS DEVELOPMENT AREA

INTRODUCTION

The Area name has been shortened from the original Production Process and Equipment Development Area to Process Development Area.

Since the start of the Project, the Process Development Area has assessed and monitored the development of those processes that showed promise of reducing processing costs significantly. Four categories of processing were identified as critical: surface preparation, junction formation, metallization, and module completion. More recently, the Process Development Area has begun integrating individual processes into complete processing sequences.

AREA OBJECTIVE

The objective of this area is to identify, assess, and develop processes and process sequences to reduce fabrication costs of reliable solar modules, and to make these processes available to the photovoltaic industrial community through technology transfer.

SUMMARY OF PROGRESS

Process Sequence Development

Two module experimental process system development units (MEPSDU) are under contract, one with Solarex Corp. and one with Westinghouse Electric Corp. These contracts had been scheduled for completion in 1982; they were modified at the beginning of May 1981 to proceed at a reduced funding rate for the remainder of the fiscal year. This reduced rate alters the contract schedules to set completion dates in 1983-1984 with no change of scope of technical duties.

Both Solarex and Westinghouse completed preliminary design reviews, including presentations by major subcontractors, in March. As a result of the review, Westinghouse will go to a frameless module design. Twelve minimodules of this design have been built and are being given environmental tests.

Solarex has replaced Kulicke & Soffa, Inc., with Tracor MBA as subcontractor for the automated soldering machine, due to cost considerations. Tracor MBA was selected from a group of solicited proposals.

Junction Formation

Work on the use of non-mass-analyzed (NMA) ion implantation has progressed to the point where it is quite clear that this process will be satisfactory for the manufacture of high-efficiency solar cells. Motorola Inc. is developing the process under private funding. Westinghouse and Spire Corp. are cooperating with JPL to establish sufficient knowledge for the development of commercial machines based on NMA ion implantation. Investigation of the source and control of contaminants, including those brought into the process by the silicon wafer itself, are continuing.

PROCESS DEVELOPMENT AREA

Spire has successfully demonstrated a 4-in.-dia capability with its pulsed-electron-beam annealing (PEBA) machine. Work is now concentrating on the development of an MMA ion implanter that is intended to be joined with the PEBA. This will allow ion implanting and annealing without breaking vacuum.

RCA Research Center has reported success in furnace-diffusing a junction into an epitaxial layer grown on a metallurgical-silicon substrate. It had been assumed for some time that the impurities in the metallurgical-grade silicon would penetrate the entire device at diffusion temperatures, forcing a departure from conventional processing.

Bernd Ross Associates have successfully produced experimental solar cells using a copper-based thick-film ink that incorporated a fluorocarbon as the fluxing agent. These cells survived 10 minutes in boiling water and retained good adhesion to the silicon. Studies of chemical reactions (involved in possible ink formulations) lead to concern over voids caused by release of gaseous products. The addition of lead acetate has provided a liquid-phase transport medium during firing that solves the void problem. Experimental data has substantiated the improvement in surface-contact conduction.

Spectrolab, Inc., has essentially completed the Midfilm metallization process contract. Two minimodules and 30 cells, 2.1 x 2.1 in., using the most promising silver-powder-based system, are being given environmental tests. Several experiments using powders based on molybdenum trioxide and tin (a technology from an earlier contract with Sol/Los) produced cells of varying low quality. A MoSn-base metallized cell of high series resistance was silver-electroplated, resulting in a cell of respectable performance. The MoSn system had successfully contacted the silicon but was highly resistive due to the limitation of the Midfilm process's thickness capability.

A new contract with Photowatt International, Inc., was executed on May 15. Photowatt will evaluate the technical feasibility and cost effectiveness of firing a metallic thick film (Ni) through an AR coat (Si_3N_4) to make electrical contact with the sun side of a solar cell. Brush-type selective plating of Cu will also be investigated. The advantages are a simplified process sequence and lower material and processing costs.

Module Completion

Tracor MBA has assembled its cell-stringing machine, lamination machine and edge-sealing machine. All discrete functions of the machines have been tested and are operational. Remaining work is focused on a software program to synchronize the operation of the total assembly.

LABORATORY ACTIVITIES

New materials supplied by the Encapsulation Task have been tested in the modified ARCO Solar, Inc., laminator. Tedlar with Du Pont Adhesive No. 68040 adhered very well to the ethylene vinyl acetate (EVA) encapsulant and a new encapsulant, ethylene methyl acrylate (EMA). After 30 minutes in boiling water, the EMA encapsulant had bubbles visible in the bulk material but no delamination or reduction in peel strength. There was no visible or mechanical degradation

of the EVA laminant after 6 hours of boiling. Peel-strength tests broke the samples without peeling failure.

Experiments are being performed with the processes specified in both MEPSDU contracts to verify their performance and to identify as many sensitive elements as possible.

ENGINEERING AREA

INTRODUCTION

The LSA Engineering Area has two primary objectives: to assist in achieving Module Technical Readiness by developing engineering design criteria, test methods, analysis tools, and trade-off data that support the engineering of optimum modules from a least-cost-array point of view, and to achieve, at an early date, technical readiness with respect to the balance of the flat-plate array subsystem exclusive of the modules.

Activities within the Engineering Area emphasized array requirements generation, array subsystem development, module development, and array-performance criteria and test-standards development. An expanded description of the status of each of the Engineering Area contracts was included in the 18th PIM Handout (JPL Document No. 5101-181). Active contracts and referenced papers and documents are listed at the end of this section.

ARRAY REQUIREMENTS

The array-requirements activity addresses the identification and development of detailed design requirements and test methods at the array level. Areas of continuing activity that address improved definition of array requirements include the establishment of module and array electrical safety criteria, the generation of intermediate-load-center building codes as applied to intermediate array design, and the development of array-to-power-conditioner electrical interfaces, coordinated with Sandia National Laboratory and The Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL).

Safety Requirements

A necessary element of module technology readiness, especially for residential and ILC applications, is the early development of safety requirements at the design level. Consistent with this goal, input obtained from the February 3 Workshop on Module and Array Safety and comments from program participants and the PV industry were used to update LSA Document No. 5101-164, "Interim Standard for Safety: Flat-Plate Photovoltaic Modules. Vol. I, Construction Requirements" (Reference 1). After updating, the document was distributed to the PV community and was specified as a supporting document for Block V procurements.

Supporting the development of array safety requirements, the National Electrical Code Ad Hoc Subcommittee on Photovoltaics (NEC AHSC) convened at JPL March 24 to 26 to draft revisions for the 1984 NEC. New articles that address the unique characteristics of a PV system and the changes needed to preclude an unsafe installation were the focus of this meeting. The PV Array working group of the NEC AHSC convened at JPL April 22 and 23 and at MIT-LL June 16 to 18 to draft the special array-related concerns for submittal to the NEC. A draft document now in review has specific areas requiring resolution (module definition, module identification, and maximum system voltage) before an NEC AHSC meeting at Westbrook, Illinois, August 11 to 13. In support of efforts toward residential roof-mounted array safety, additional roof-covering classification

and fire-penetration tests are scheduled at Underwriters Laboratories on August 14 to determine a PV module's resistance to severe fire exposures from sources outside a building. Included are shingle and integral-mount residential-module designs.

Progress in array safety was documented in a paper presented at the American Section, International Solar Energy Society (AS ISES) meeting May 26, titled "Code-Related Considerations for Flat-Plate Photovoltaic Arrays" (Reference 2).

Commercial and Industrial Building Codes

In support of the development of intermediate-load array-design guidelines, Burt Hill Kosar Rittelmann Associates completed their assessment of intermediate-load-center building codes and regulations (initial results were presented at the 17th PIM). An executive summary and clarifying points are being added to the final report, which is scheduled for release September 15.

Power-Conditioning Interface

Selection of the optimum input voltage window for power conditioning is influenced by array voltage fluctuations caused by site weather conditions. A JPL in-house analysis, using solar radiation surface meteorological observations (SOLMET) typical-year data tapes, generated input for determining the optimum power-conditioning voltage, current and power levels vs array parameters. The completed data were provided to Sandia National Laboratory for both residential and intermediate-load applications. Tabulated data on array power-conditioner interface optimization will be included in Sandia's Power Conditioning Specification.

ARRAY SUBSYSTEM DEVELOPMENT

Array subsystem development activity is focused on the development of conceptual designs for integrated flat-plate array/module support structures as an important approach to minimizing total array costs. A critical output of array conceptual designs is the definition of specific design requirements addressed to functional performance, interface and maintainability (at the array level).

Integrated Residential Arrays

A number of residential array conceptual designs were evaluated during the reporting period through contracts with the American Institute of Architects Research Corp. (AIA/RC) and General Electric Co. (GE). Design reviews in conjunction with the integrated residential array effort were held February 17 and 18, March 19 and 20, and April 29 and 30.

AIA/RC reviewed the 15 conceptual designs generated by their architect subcontractors. The AIA/RC advisory committee, consisting of Solarex Corp., Heery Energy Consultants, National Association of Home Builders Research

Foundation and Energy Design Associates representatives, then selected three concepts for design optimization. Evaluations of these designs were completed and AIA/RC recommended the Burt Hill Kosar Rittelmann Associates design for final design and fabrication.

After evaluating 19 different module/array types, GE optimized three concepts: direct-mounted, overlapped, rectangular shingle; integral mount with plastic tray, and stand-off mount with aluminum frame. Further evaluation of these concepts resulted in approval of GE's optimized "universally mountable" design using a rolled-steel support. Refinement of this concept is in progress, with emphasis on reducing costs of array installation and module production.

JPL Engineering Area in-house efforts on residential module installation methods included the construction of six 4 x 4-ft panel frames (one module each) and a 45° test roof with a 16-ft slant height and a 12-ft width. Preliminary tests have shown a library-type rolling-ladder configuration to be convenient and to provide adequate access for module installation and replacement. Both aluminum and wooden frame module supports are being tested.

Large Ground-Mounted Arrays

In support of optimized large ground-mounted array design, a task report titled "Low-Cost Solar Array Structure Development" (Reference 3) was completed and distributed to the PV community. The report included cost analyses, durability and earthquake loading assessments based on modal testing.

Photovoltaic/Thermal Arrays

In the area of photovoltaic/thermal module development, an economic study that included installation costs showed the PV/T unglazed collector system to be marginally economical (life-cycle savings of $600 over 20 years). The study is being documented and further PV/T work is deemed unjustified.

MODULE ENGINEERING

Module engineering addresses the development of design methods, analysis tools and design concepts necessary to support significant cost and performance improvements at the array-element level. Activities are conducted to clarify design tradeoffs, to develop analysis tools and test methods and to provide generalized design solutions for the PV community. Specific activities included cell reliability testing, module voltage isolation, interconnect fatigue, hot-spot endurance, cell-fracture mechanics, module soiling and module environmental endurance.

Cell-Reliability Testing

The Clemson University contract, which has been developing reliability and accelerated-stress test data on most of the solar-cell types now being used in LSA module designs, included evaluation of newly developed cells that have

low-cost potential (due primarily to the type of metallization system used). Among the new cells received, those that use copper-based metallization systems show evidence of reduced mechanical strength on the lead attachments and low metal-to-silicon adhesion.

Module Voltage Isolation

The voltage isolation task addresses the source and magnitude of leakage currents to ground caused by initial insulation flaws or material aging. The development effort is directed toward predictions of module life and providing for human safety. Activities included:

The high-voltage field-test stand was upgraded to 3000 Vdc for use in continuing central-station module field-exposure insulation studies. In support of these tests, two experimental modules were instrumented with temperature and moisture (vapor) sensors and were calibrated under nine different combinations of temperature and relative humidity while under 3000 V electrification. Data reduction is in progress and the results will identify responses of both room-temperature vulcanized (RTV) and ethylene vinyl acetate (EVA) encapsulants.

The initial cell-string flaw-characterization tests were completed. Solar-cell electrodes used to break down air gaps of various sizes were observed to exhibit deviations from uniform field conditions, both at small gap separations (point-to-plane effects) and at large gap separations (square-edge effects).

Construction of a low-voltage film breakdown apparatus was completed and underwent preliminary testing with single-layer and multilayer polymer films. The data reduction system is being improved to permit higher data rates.

The electrical-insulation environmental-life test chamber for minimodules has been completed, less power and data collection circuitry.

Procurement of minimodules representing recent module designs (Block IV, PRDA and commercial) has been initiated, encompassing approximately 100 modules for environmental and life testing.

This work was documented in the 1981 Institute of Electrical and Electronics Engineers (IEEE) Photovoltaic Specialists Conference paper "Defect Design of Insulation Systems for Photovoltaic Modules" (Reference 4).

Interconnect Fatigue

Examination of the mechanical-fatigue life of cell interconnects is continuing in an effort to obtain a 20-year life-prediction model. Two parts of a report on cell-interconnect fatigue have been drafted: strain prediction and allowable strain analyses, and a cost-optimization algorithm. A nomograph on determining strain from interconnect-shape parameters was developed for presentation at the 18th PIM. In support of this effort, a three-axis micrometer-comparator to measure interconnect geometries <u>in situ</u> has been designed and

built. This device will be used on modules undergoing thermal cycling to determine their geometries and their condition (e.g., breakage).

Hot-Spot Endurance

This activity's objective is development of suitable laboratory test procedures for evaluation of the hot-spot endurance of a module under severe hot-spot field conditions. Development activities included the collection of laboratory data from Block III modules for validating the analytical thermal model under development. The thermal model supports the development of module design guidelines for hot-spot endurance capability. Agreement between the model and test data has been generally close for both insulated- and uninsulated-back modules. Limits of model applicability are being developed and additional hot-spot tests are planned to validate the laboratory test procedures. A task report on hot-spot heating design guidelines is scheduled for December release. This effort was also documented in the 1981 IEEE PV Specialists Conference paper "Photovoltaic Module Hot-Spot Durability Design and Test Methods" (Reference 5).

Cell-Fracture Mechanics

Efforts in the fracture mechanics study of Si solar cells centered on the design of a mechanical-strength-testing jig. The prototype testing jig is designed to evaluate the feasibility of a quality-control method for Si wafers and cells, based on testing their mechanical strength. Results were reported in a PV Specialists Conference paper, "Application of Fracture Mechanics to the Failure Analysis of Photovoltaic Solar Modules" (Reference 6).

Module Soiling

Module soiling studies continued with samples measured from 70% of the field-test sites. The trends exhibited after six months in the field this year closely follow those established during the previous year of field exposure. JPL in-house research also included low-cost cleaning methods for arrays, using both water and chemical-cleaner spray washes. A chemical cleaner proved superior to multiple water washes on glass samples with oily films, increasing the relative normal hemispherical transmittance from 87% to 99%. The upper limit was 94% using water washes.

Module Environmental Endurance

Several environmental-endurance development efforts are being addressed to provide the technical base required to achieve reliable modules with 20-year lifetimes. The Illinois Institute of Technology Research Institute (IITRI) is continuing its work in compiling reliability data on all module design technologies vs design technology performance in both field use and field tests. A major input to the IITRI work was initiated when the U.S. Coast Guard Research and Development Center agreed to provide LSA with reliability data obtained from different module designs it has tested.

ENGINEERING AREA

JPL in-house efforts included the development of detailed test methods for salt-spray testing in both outdoor and lab test environments, and a humidity-degradation rate curve based on comparisons of humidity testing cycles and humidity-temperature data from SOLMET weather tapes. To obtain the required temperature-humidity acceleration factors, a contract was initiated with Wyle Laboratories to subject Block I and Block III modules to six-month humidity tests with environments of 40°C, 93% RH and 85°C, 85% RH.

A review of the overall module test program at JPL was presented at the 1981 Institute of Environmental Sciences Conference in a paper, "Outdoor and Laboratory Testing for Photovoltaic Modules" (Reference 7).

PERFORMANCE CRITERIA AND TEST STANDARDS

Active interfaces are maintained between LSA Engineering activities and the Solar Energy Research Institute (SERI) Performance Criteria-Test Standards (PC/TS) project to draft interim performance criteria and standards covering both flat-plate and concentrator arrays.

In support of the SERI project, the Array Subsystem Task Group convened at JPL February 2 and at Motorola Inc., Government Electronics Division (GED) March 18 and 19 to update the "Interim Performance Criteria for Photovoltaic Energy Systems" report distributed by SERI (No. SERI/TR-742-654). Emphasis was placed on the review of new and redrafted criteria and test methods in personal safety, durability and reliability, and concentrator electrical performance. The task group presented 12 criteria statements, three test methods and 18 definitions to SERI, who will publish the second edition (now in review) of the Interim Performance Criteria document (IPC-2) in December.

The Electrical Performance Subgroup of the Array Subsystem Task Group (led by Arizona State University) met at JPL February 3, at Motorola GED March 17 and at Orlando, Florida, May 11 to 15, to determine acceptable test methods for measuring optical performance of reflective concentrators. The lens test methods are being prepared for Task Group submittal.

Also in support of SERI's Performance Criteria and Test Methods Project, JPL formed a Photovoltaic Environmental Subgroup to review and document environmental test methods for array subsystem elements. JPL, Sandia, the U.S. Department of Defense, and foreign organizations are evolving environmental-test requirements and methods for photovoltaics that should be examined in detail by a cadre of outdoor and laboratory testing experts. The objective of the subgroup is to develop for flat-plate and concentrator array elements a cost-effective set of environmental qualification test procedures that can provide reasonable assurance of reliable performance in a wide range of climates. The first meeting of this subgroup was held at JPL July 14.

ENGINEERING SUPPORT

Engineering interface activities provide for transfer of array requirements, specifications, conceptual designs, design guidelines, analysis tools and test methods to the photovoltaic community. R. G. Ross Jr., Engineering Area manager, lectured on module and array engineering at a three-day short

course on photovoltaics conducted by Arizona State University. The presentation was later embodied in two IEEE PV Specialists Conference papers titled "Design Techniques for Flat-Plate Photovoltaic Arrays" and "Photovoltaic Module and Array Reliability" (References 8 and 9). Additional past work on the probability statistics of cloudy days was presented at AS ISES in a paper, "Techniques for Determining Solar Insolation Deficits" (Reference 10).

A matrix comparing design features of photovoltaic modules in field applications and LSA procurements was generated. The matrix, intended to facilitate comparisons of design and test history data, includes module types with materials of construction; cell types with materials used for inter-connects and metallization, coatings, etc.; module and system circuit (series-parallel) configurations that identify series blocks, blocks per diode, etc., and specific problems encountered in both field and laboratory tests. It will be continually updated.

JPL's Engineering Area staff participated in the MIT-LL Residential PIM in Cambridge, Massachusetts, on June 24-25, 1981. Presentation topics included LSA Project Update, Block V Performance Requirements, and Integrated Array Designs. Presentations made at the Photovoltaic System Definition and Development PIM at Sandia April 8 included "Photovoltaic Array Safety Requirements."

Module design specifications were developed, including "Block V Solar Cell Module Design and Test Specification--Intermediate-Load Applications" and "Block V Solar Cell Module Design and Test Specification--Residential Applications." These documents were released February 20 as part of the Block V RFP (References 11 and 12). A preliminary draft of the Central-Station Module Design and Test Specification was circulated for LSA in-house review.

REFERENCES

1. Interim Standard for Safety: Flat-Plate Photovoltaic Modules; Vol. 1, Construction Requirements, JPL Document No. 5101-164, February 20, 1981.

2. Sugimura, R. G., and Levins, A., "Code-Related Considerations for Flat-Plate Photovoltaic Arrays," AS ISES Conference, May 26, 1981.

3. Wilson, A. H., Low-Cost Solar Array Structure Development, JPL Document No. 5101-165, June 15, 1981.

4. Mon, G. R., "Defect Design of Insulation Systems for Photovoltaic Modules," 15th IEEE PV Specialists Conference, May 12, 1981.

5. Arnett, J. C., and Gonzalez, C. C., "Photovoltaic Hot-Spot Durability Design and Test Methods," 15th IEEE PV Specialists Conference, May 12, 1981.

6. Chen, C. P., and Leipold, M. H., "Application of Fracture Mechanics to Failure Analysis of Photovoltaic Solar Modules," 15th IEEE PV Specialists Conference, May 12, 1981.

7. Hoffman, A. R., Jaffe, P., and Griffith, J., "Outdoor and Laboratory Testing of Photovoltaic Modules," IES Conference, May 6, 1981.

8. Ross, R. G., "Design Techniques for Flat-Plate Photovoltaic Arrays," 15th IEEE PV Specialists Conference, May 12, 1981.

9. Ross, R. G., "Photovoltaic Module and Array Reliability," 15th IEEE PV Specialists Conference, May 12, 1981.

10. Gonzalez, C. C., and Ross, R. G., "Techniques for Determining Solar Insolation Deficits," AS ISES Conference, May 26, 1981.

11. Block V Solar Cell Module Design and Test Specification--Intermediate Load Applications, JPL Document No. 5101-161, February 20, 1981.

12. Block V Solar Cell Module Design and Test Specification--Residential Applications, JPL Document No. 5101-162, February 20, 1981.

RECENT CONTRACTOR PUBLICATIONS

1. Safety and Liability Considerations for Photovoltaic Modules/Panels, Report No. DOE/JPL 955846-81/1, Prepared for JPL by Carnegie-Mellon University, Pittsburgh, Pennsylvania, January 1981.

2. Wind Loads on Flat Plate Photovoltaic Array Fields, Report No. DOE/JPL 954833-81/3, Prepared for JPL by Boeing Engineering and Construction Co., Seattle, Washington, April 1981.

3. Integrated Residential Photovoltaic Array Development, Quarterly Report No. DOE/JPL 955894-2, Prepared for JPL by General Electric Co., Advanced Energy Programs, Philadelphia, Pennsylvania, May 1981.

4. Integrated Residential Photovoltaic Array Development, Quarterly Report No. DOE/JPL 955893-81/1, Prepared for JPL by AIA Research Corp., Washington D.C., April 1981.

OPERATIONS AREA

INTRODUCTION

The overall objectives of the Operations Area are to stimulate the use by module manufacturers of the latest improvements and innovations in module production and design technology through contracts for development of qualified solar-cell modules; to perform appropriate environmental and stress tests to confirm the adequacy of module design; to operate field-test sites to accumulate the data needed to establish the kinds and levels of environmental stress tests required to qualify modules; to perform failure analysis on modules that have failed either in the field or during qualification testing to provide guidance for proper corrective action, and to provide testing and failure analysis services and facilities as required to support other DOE test and applications experiments.

MODULE DEVELOPMENT

Block IV Design and Qualification

Only small progress has been made toward completing the design and qualification phase of the Block IV effort. In the ARCO Solar, Inc., intermediate-load module, the butyl edge sealant, which had softened and flowed during thermal cycling, was replaced by a new acrylic copolymer sealant. Modules with this sealant successfully completed all of the pertinent qualification tests. Drawings for the ARCO residential modules were approved and modules were delivered to JPL for testing. Before testing could be started, ARCO requested permission to substitute for the delivered modules a new set using a Tedlar front cover of twice the thickness previously used, in an effort to overcome an edge-delamination problem that had appeared on similar modules tested for the Southwest Residential Experiment Station (RES). The Photowatt International, Inc., module that failed the test program has had design changes and new modules are being fabricated. Solarex Corp. modules of both intermediate-load and residential configurations have been submitted for testing, but none has passed.

Block IV Production Contracts

Purchase orders for a few kilowatts of modules designed and qualified under the provisions of the Block IV design contracts have been placed with all of the contractors. A contract for the ARCO intermediate-load module was placed, late in this reporting period, but no order has been placed for the residential module. General Electric Co. and Motorola Inc. have delivered all modules required by purchase orders placed with them. Applied Solar Energy Corp. and Spire Corp. have made partial delivery of the modules ordered from them. All other orders for modules are under a contractually imposed hold until tests are completed and the final design documentation is in order. This hold pertains to the Photowatt modules and both Solarex (residential and intermediate-load) modules. No modules of the Block IV design were produced for sale by Solar Power Corp., but a laminated module of their commercial configuration that had been altered to conform to the Block IV specification passed all the qualification tests.

OPERATIONS AREA

Block V Design

The RFP for the Block V competition was released to 29 potential proposers in February. Fourteen organizations proposed 19 different module designs, which were evaluated and rated. Selections were made and seven contracts were negotiated as follows:

Intermediate-Load Modules:

ARCO Solar
RCA
Solar Power Corp.
Solarex

Residential-Load Modules:

General Electric
Mobil Tyco Solar Energy Corp.
Spire

MODULE TEST AND EVALUATION

Performance Measurements

New reference cells have been selected, fabricated and calibrated for Block IV modules manufactured by ASEC, GE and Photowatt because latest versions of their modules and original reference cells no longer matched in spectral response. In addition, new reference cells have been selected, fabricated and calibrated for use by Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL) in testing ASEC, ARCO, Solec International, Solarex, Motorola, Photowatt, and Spire (photovoltaic/thermal) modules. Several Block II and Block III reference cells were recalibrated at JPL for use by DSET Laboratories, Inc., and Wyle Laboratories. Forty-three additional reference cells are being selected, fabricated and calibrated for use by JPL Field Testing, Sandia National Laboratory and Solenergy Corp.

The large-area pulsed solar simulator (LAPSS) No. 2 is continuing to function properly and is being used primarily for Encapsulation Task module evaluation, reference-cell evaluation and selection, and miscellaneous engineering measurements. LAPSS 1 is presently being integrated with the PDP 11/60 computer. All required hardware has been completed and final system evaluation is nearly complete. Preliminary comparison tests indicate an even closer agreement between the two LAPSS systems than previously reported. The color temperature of LAPSS 2 was found to be somewhat higher than that of LAPSS 1, resulting in an increase in illumination in the blue portion of the LAPSS 2 spectrum.

The PDP software has been modified to allow the storage of parameter tables unique to each type of module under evaluation. This greatly reduces operator error and significantly increases throughput by reducing the time required for the operator to enter or modify a specific module's parameter table. New tables can be added or deleted easily.

OPERATIONS AREA

Environmental Testing

Testing is continuing or has been completed on Block IV, MIT-LL Residential Experiment Station, Program Research and Development Announcement (PRDA)-38 retest, World Bank, Process Development Area, and commercial modules. The results are given in Tables 3, 4, and 5. In addition to the familiar Block IV tests, two hot-spot test stations have been set up in Building 248-2. Hot-spot tests, called out in the Block V Design and Test Specification, have been run on MIT-LL RES, PRDA-38, World Bank, and Block IV types of modules.

Qualification testing is still under way on Block IV modules. Six types are considered to have qualified and four are not. Most module types did not pass the first time and improved designs had to be submitted by the manufacturers. The six qualified types averaged two sets of tests and the still-to-be-qualified types have averaged three sets. Tests run on samples drawn from the lots of modules purchased after qualification indicate that the level of quality of the module has not been maintained. Some significant degradation has occurred, which casts doubt on the ability of the manufacturers to maintain quality of product consistently. All modules given the new hot-spot test passed except two, MIT-LL GR and World Bank UU. Encapsulant bubbles and discoloration are common. Of the failed modules, the common failure mode is a reduction of shunt resistance (partial shorting) of the cells. No catastrophic failures have occurred.

Field Tests

For a combination of fiscal, logistic and technical reasons, a major restructuring of field-test activity was required. Since the 17th Project Integration Meeting in February a plan was formulated and is being implemented. Details of this plan were presented at the 18th PIM.

Most of the effort since the 17th PIM has centered on the restructuring of, and especially on reorganizing, the test sites. A key feature of the restructuring is that the Blocks I, II, and III modules now deployed at the local sites will either be transported to an enlarged Goldstone site for continued testing (on a time-available basis) or surplussed. On June 19 the last set of routine data was obtained on these modules at the JPL site. An analysis of the electrical performance data for the past eight months indicates that nine additional modules failed since October of 1980 and that 32 of the remaining 211 modules are now degraded. A summary of the electrical performance data is presented in Table 6. Using a new analysis program that factors out the effects of embedded dirt on performance, the mean power decrement of the degraded modules was determined. Table 7 contains a breakdown of this information.

To obtain an update of all the modules at the local sites before their relocation, electrical performance data also was obtained on the Goldstone and Table Mountain modules (the Point Vicente modules were stolen in March of 1981). Of the original 162 modules deployed at the two sites several years ago, 12 failed before October 1980. Four other modules have failed since then. Three of these are Block I Solar Power modules at Goldstone. Of the remaining 146 modules, 10 have degraded.

Table 3. Recent Qualification Test Results: Block IV Modules

Vendor Code/Number of Modules Tested	Construction (From Top Down)	Principal Problems
RQ/4 Production	Glass, PVB, Tedlar/Al/Tedlar, stainless frame	Block IV test: increased circuit resistance during cold temperatures, delamination at feedthrough washers; frame weld broken during wind simulation; resistance rise (12%) during twist test
RQ/6 Production	Glass, PVB, Tedlar/Al/Tedlar, stainless frame	Back-surface delamination and at feedthrough washer after temperature cycling; Block V hot-spot test produced minor discloration around cells
US/4	Glass, PVB, Tedlar/steel/Tedlar, Al frame	Third set of modules tested satisfactorily except for one small cell crack
VS/5	Glass, PVB, Tedlar/Al/Tedlar, Al frame	Continuing frame separations, three modules; one cell crack in wind simulation; electrical degradation and shorting of diodes attributed to faulty LAPSS connector; diode design to be changed
YR/2 YS/3	Glass, EVA, Tedlar, no frame Glass, EVA, Tedlar, Al frame	Continuing backside delamination and bubbles; previous cell shifting not present on latest modules
ZJ/4	Glass, encapsulant, Tedlar, Al side rails, plastic ends	Commercial module substitute for Block IV design passed tests satisfactorily
MQ/2 Production	Glass, PVB, Tedlar, Al frame	Glass to encapsulant delamination noted first after humidity cycling, then noted in virgin modules after storage for several weeks; contaminated glass or improper curing cycle suspected

Table 4. MIT-LL RES Block IV Tests, Plus Hot-Spot Test (One Module)

Vendor Code/Number of Modules Tested	Construction (From Top Down)	Principal Problems
GR1/1	Glass, adhesive, RTV, weatherproofed paperboard	Hot-spot: severe cell degradation, bubbles over cells to 3 cm, amber discoloration at cell edges, collector discoloration
GR2/3	Glass, adhesive, RTV, weatherproofed paperboard	Built-up three-module roof tested in temperature cycling: dummy shingles delaminated and shrank, amber discoloration around cells; interconnect discoloration; 6% degradation
M1/2	Glass, PVB, Tedlar, Al frame	Wind simulation performed this period; 7% electrical degradation, both modules
M2/1	Glass, PVB, Tedlar, Al frame	J-boxes warped, Tedlar discoloration over J-box, bubbles after temperature cycling; power instability after wind simulation
R1/3	Glass, PVB, Tedlar/Al/Tedlar, stainless frame	Delamination at feedthrough washers after temperature cycling; five frame corner welds broken after humidity on three modules; one cell crack
R2/3	Glass, PVB, Tedlar/Al/Tedlar, stainless frame	Delamination at feedback washers; back-surface Tedlar delamination after humidity
UR/2	Tedlar, EVA, galvanized steel pan, mounted in JPL wooden frame	Temperature: one cell crack; humidity: delam of top cover at edge of module, delam between and over cells, one cell crack; hail, many fine cell cracks; hi-pot, one failure
US/2	Glass, PVB, Tedlar/steel/Tedlar, Al frame	Initial hi-pot failures (ungrounded back surface)

Table 4. MIT-LL RES Block IV Tests, Plus Hot-Spot Test (One Module) (Continued)

Vendor Code/Number of Modules Tested	Construction (From Top Down)	Principal Problems
YS1/2	Glass, EVA, Tedlar, Al frame	Hail test: one cell crack
YS2/2	Glass, EVA, Tedlar, Al frame	Temperature: bubbles; cells shifted and touching; bus bar to IC broken, 56% electrical degradation, one module; humidity: 25% degradation, one module delamination over cells and back surface, one cell crack
YS3/2	Glass, EVA, Tedlar, no frame	Temperature: shifted cells, cells touching, electrically unstable, bubbles; humidity: Tedlar delamination; wind simulation: edge seal loose

Table 5. Other Types of Modules

Vendor Code/Number of Modules Tested	Construction (From Top Down)	Principal Problems
PRDA-38 Retest, Block IV Test, Plus Hot-Spot (One Module)		
ZF/4	Glass, RTV, white Mylar, Al frame	Some electrical degradation and recovery by the end of testing; hot spot test: satisfactory
World Bank, Hot-Spot Test Only		
FU/1	Glass, encapsulant, glass, Al frame	Satisfactory
IU/1	Glass, Space, encapsulant, Al substrate and frame	Satisfactory
YU/1	Glass, silicone, white silicone, Al frame	Satisfactory
UU/1	Glass, PVB, Tedlar/steel/Tedlar, Al frame	Bubbles over cells, backside Tedlar delamination, one cell degraded (partial short) but only 2% module degradation
PD, Block IV, no hail		
UT/4 (Automated Soldering)	Glass, PVB, Tedlar/steel/Tedlar, Al frame	Edge-sealant extrusion
WT/1	Glass, Craneglass, EVA, cells, Craneglass, white EVA, Craneglass, 1 mil Al/polyester film	Back-surface blistering, 28% electrical degradation in temperature cycling; degradation increased to 38% after humidity cycling

Table 5. Other Types of Modules (Continued)

Vendor Code/Number of Modules Tested	Construction (From Top Down)	Principal Problems
Commercial, Temperature and Humidity Tests Only		
LO/4	Glass, encapsulant, Al foil, black insulating material, Al frame	Interconnects were damaged as received; temperature cycling caused 5% degradation on one, delamination above cells, and a J-box pottant leak on one
BNO/4	Glass, encapsulant, stainless substrate and frame	5% electrical degradation in humidity cycling, one module

Table 6. Electrical Performance Status of JPL Modules, June 19, 1981

Module Type	Number Orginally Deployed	Deployed	Number Failed as of 9/80	Number Failed Since 9/80	Number Currently Degraded
Sensor Tech I	64	10/76 to 12/78	8	3	4
Spectrolab I	41	10/76 to 5/78	4	0	8
Solarex I	39	10/76 to 11/77	8	1	1
Solar Power I	21	10/76 to 12/78	16	0	1
Sensor Tech II	34	2/77 to 8/77	2	1	14
Spectrolab II	13	5/77 to 11/77	0	0	0
Solarex II	19	6/77 to 12/78	3	4	0
Solar Power II	14	5/77 to 10/77	2	0	3
Arco Solar III	10	10/78	0	0	0
Motorola III	8	10/78 to 2/79	0	0	1

Table 7. Breakdown of Degraded JPL Modules by Type and Power Decrement

	Peak-Power Decrement (%)				
Module Type	0 to 3	3 to 5	5 to 10	10 to 15	15 to 25
Sensor Tech I	2	1	1		
Spectrolab I		4	4		
Solarex I	1				
Solar Power I		1			
Sensor Tech II	3	2	3	4	2
Spectrolab II					
Solarex II					
Solar Power II	1		2		
Arco Solar III					
Motorola III				1	

Other significant accomplishments:

1. The decommissioning of the 12 continental remote sites (in accordance with the restructuring plan) was started and is well under way. Contracts are being let to the resident site managers to remove and ship the test modules to JPL, and to remove the stands from the ground. Completion of the decommissioning is expected by the end of September.

2. Plans are proceeding to establish a hot, humid environmental-test site (in accordance with the restructuring plan). A two-phase contract was let to the Florida Solar Energy Center at Cape Canaveral for the site. The first phase covers the installation of test stands and the establishment of the site at their facility; it should be completed in mid-September. The second phase covers routine monthly inspections of the modules to be deployed at the site.

3. Expansion of the Goldstone site was completed in July. The site was enlarged to accommodate 30 additional 4 x 4-ft test units, which will be used to support the old modules. A security fence will be installed around the site's perimeter. It is expected to be in place by the end of September.

4. Removal of the hundreds of feet of wiring for the old modules at the JPL site was started and completed in July. Rewiring of the site for the Block IV modules, in accordance with the restructuring plan, is expected to be done by the middle of October, contingent upon availability of materials.

5. In-house fabrication of a battery-powered array data logger, capable of collecting data and providing diagnostics on 40-A, 400-V arrays, was initiated. Completion of this instrument is expected by the end of September.

Failure Analysis

Problem and failure analysis activity continued to provide failure-analysis support to the test and applications experiments of MIT-LL and Lewis Research Center (LeRC), and also to the JPL field and environmental test activities. Additional failed Block II and III Solarex modules from Bryan, Ohio, and Schuchuli, Arizona, were confirmed to have failed because of broken interconnects, as reported previously. MIT-LL submitted two Solarex modules from the Carlisle house because of voltage breakdown. The problem was caused by moisture ingress to voids in the edge seal and the module wire layout. MIT-LL also sent an ARCO module from the Westinghouse Northeast RES that exhibited excessive leakage current to ground. It was determined that the foil vapor barrier was floating, providing a series capacitance and allowing a large voltage to develop between foil and ground. Grounding the foil transfers the voltage stress to the encapsulant and the withstanding voltage could be increased from 800 Vdc to 3500 Vdc without exceeding the allowable leakage current. Finally, MIT-LL reported concern over leakage currents in ARCO modules used in the Hawaiian residences. This report is under review and study by failure analysis and engineering activities.

Block IV modules continued through qualification testing and suffered some failures. Photowatt modules experienced erratic power measurements and decreases in power after the environment tests. The erratic power measurements were traced to momentary overloading of the bypass diodes by the LAPSS in the process of curve tracing coupled with marginal diode current-carrying capacity. Further analysis showed shorting of the top and bottom surfaces of the cell. A laser scan is used before module testing to confirm cell matching and to discover shorted cells. Solarex modules have undergone extensive analysis effort. The problems encompassed uncured EVA, delamination of Tedlar back surface from EVA, cell back-contact metal not adhering to silicon, shorted diodes, shorted cells, inadequate de-aeration of the laminate and dielectric breakdown between frame and cell strings.

APPLICATIONS INTERFACE

Test and Applications support was provided as follows:

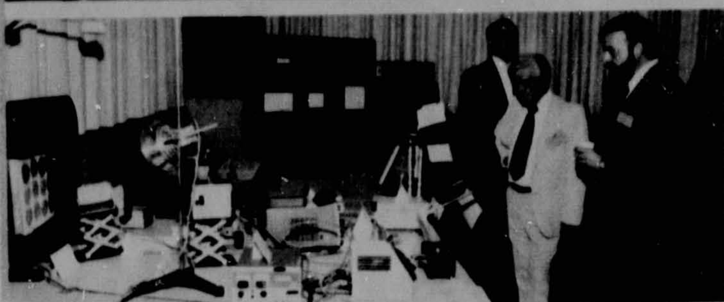
1. Attendance and follow-up support to 12 quarterly and critical-design reviews at Sandia for PRDA applications, and at MIT-LL for residential applications.

OPERATIONS AREA

2. Coordination and follow-up support of module qualification testing for the MIT-LL residential-applications experiments.

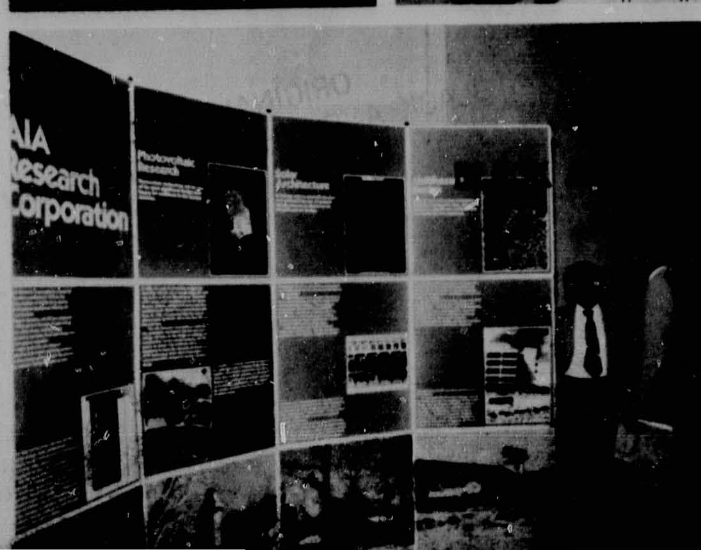
3. Coordination and follow-up support of module-failure analysis of field failures at various MIT-LL and LeRC installations.







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PROCEEDINGS

INTRODUCTION

The Low-Cost Solar Array (LSA) Project convened its 18th Project Integration Meeting (PIM) at the Pasadena Center on July 15-16, 1981.

The theme for this PIM was dual in nature--Perspectives for Progress, and Module and Array Long-Life Performance. This dual theme was believed to be timely in view of technical achievements to date. Viewpoints of the Project, the government, users and manufacturers on the status of photovoltaics development and its future needs were presented.

Emphasis was placed on displays showing the current status of technical advancements.

AGENDA

WEDNESDAY: July 15, 1981

8:30	Welcome and Announcements	Callaghan, Magid	
8:40	Perspectives for Progress	W. Callaghan	p. 53
9:25	PV Users Viewpoints on Modules & Arrays	Matlin (TriSolar)	p. 58
		Brown (AZ Pub. Serv.)	p. 63
10:40	Performance & Reliability of Modules & Arrays	Evans (JPL)	p. 67
11:10	Future Technology Needs	Wolf (U. of PA)	p. 77
11:40	Evolving Module and Array Technology	Ross (JPL)	p. 94
1:30	Industry Perspectives for Next Five Years	McGinnis (Photowatt)	p. 100
2:30	Wafering Workshop Summary		p. 104
3:30	Technology Sessions (Parallel)		
	Silicon Material	Lutwack	p. 111
	Large-Area Silicon Sheet	Liu	p. 139
	Encapsulation	Coulbert	p. 241
	Process Development	Bickler	p. 295
	Engineering and Operations	Ross, Runkle	p. 405
3:30	Quality Assurance Workshop	Anhalt	

THURSDAY: July 16, 1981

8:00	Technology Sessions (Parallel)		
	Silicon Material	Lutwack	p. 111
	Large Area Silicon Sheet	Liu	p. 139
	Encapsulation	Coulbert	p. 241
	Process Development	Bickler	p. 295
	Engineering/Operations	Ross, Runkle	p. 405
1:15	Parallel Activities		
	Technology Transfer	Gallagher	p. 401
	Module Reliability Forum	Ross, Runkle, Forman	
	Energy Payback Time, Spinoff Benefits, Environmental Control	Aster, Gershman	p. 548
2:45	Looking in on Photovoltaics	Maycock (REI)	
3:15	Summaries: LSA Lead Center DOE		p. 561
4:30	End of Meeting		

Plenary Session

PERSPECTIVES FOR PROGRESS

JET PROPULSION LABORATORY

W.T. Callaghan

The Work Remaining

- **PROJECT WILL FOCUS ON TECHNICAL FEASIBILITY TO:**
  - **ASSUME TECHNICAL RISKS THAT INDUSTRY WILL NOT ASSUME**
  - **EFFECT TRANSFER OF TECHNICAL FINDINGS TO INDUSTRY**
- **MEASURE OF SUCCESS IS**
  - **DETERMINED BY THE ADOPTION RATE OF INFORMATION AND ITS USEFULNESS TO INDUSTRY**
  - **PHOTOVOLTAIC POWER BECOMING COMPETITIVE**

Specific Work Remaining in the Project

- **SILICON MATERIAL REFINEMENT**
- **SHEET MATERIAL FORMATION**
- **ENCAPSULATION**
- **PROCESS RESEARCH AND DEVELOPMENT**

Silicon Material

- LOW-COST MATERIAL IS VERY IMPORTANT TO INDUSTRY
- NO LOW-COST MATERIAL SOURCE EXISTS FOR INDUSTRY
- MATERIAL COMES FROM SEMICONDUCTOR INDUSTRY AT SEMICONDUCTOR PRICES: $60 - $80 / kg
- LOWER-COST REFINEMENT PROCESSES REQUIRES BOTH LOWER-COST FEEDSTOCK AND DEPOSITION TECHNOLOGY,
- PROJECT, THROUGH INDUSTRY, HAS DEMONSTRATED NEW TECHNOLOGICAL PATHS TOWARD ACHIEVING BOTH REQUIREMENTS

  - WHAT REMAINS TO BE DONE:
    - DEMONSTRATE TO INDUSTRY WITH SUFFICIENT CONFIDENCE THAT THE TECHNOLOGY FEASIBILITY IS SHOWN I.E.,
      - REPRODUCIBLE
      - SCALABLE TO INDUSTRIAL PROPORTIONS
      - PROFITABLE
  - THE MEASURE OF SUCCESS IS INDUSTRIAL ADOPTION AND AVAILABILITY OF SILICON TO THE PHOTOVOLTAICS INDUSTRY

Sheet-Material Formation

- INDUSTRY STANDARD IS SEMICONDUCTOR-INDUSTRY INGOT WAFER
    - ERRATIC SUPPLY
    - UNPREDICTABLE PRICE
    - HIGHLY VARIABLE QUALITY

- PROJECT, THROUGH INDUSTRY, HAS DEVELOPED ADVANCED INGOT TECHNOLOGICAL PATHS
    - PRODUCES HIGH-QUALITY SHEET MATERIAL
    - AT LOWER PRICE
    - WITH GREATLY INCREASED THROUGHPUT RATES

- ADVANCED INGOT WORK IS EXPECTED TO BE ADOPTED BY INDUSTRY

- THE LONGER-TERM, TRULY LOW-COST SHEET TECHNOLOGIES ARE MATERIAL-CONSERVATIVE; DRAWN RIBBON IS A PROMISING TECHNICAL APPROACH FOR WIDESPREAD U.S. ENERGY USAGE

- WORK REMAINING:
    - INVESTIGATE PROCESS EFFECTS ON CRYSTALLIZATION LEADING TO IMPROVEMENT IN SHEET QUALITY
    - UNDERSTAND BASIC LIMITATIONS OF SILICON-SHEET MATERIAL QUALITY AND ITS EFFECT ON SOLAR CELL PERFORMANCE
    - INVESTIGATE CRITICAL FACTORS FOR HIGH THROUGHPUT OF MULTIPLE, THIN, FLAT AND WIDE RIBBON
    - STUDY PROCESS PARAMETER LIMITS AND SEQUENCES TO DEVELOP AUTOMATED GROWTH WITH MELT REPLENISHMENT
    - TRANSFER TECHNOLOGICAL INFORMATION FOR INDUSTRY ADOPTION

Encapsulation

- PROTECTIVE MATERIAL FOR TERRESTRIAL PHOTOVOLTAICS WAS:
  - EXPENSIVE
  - SHORT-LIVED
  - HIGHLY VARIABLE IN DESIGN
- PROMISING MATERIAL COMBINATIONS OFFER POTENTIALLY LOWER COST AND LONGER LIFE SUCH AS:
  - LOW-IRON GLASS TOP COVER
  - EVA OR PVB POTTANT
  - GLASS OR MYLAR/TEDLAR BACK COVER
- THE WORK REMAINING:
  - IDENTIFY AND CONTROL BASIC DEGRADATION MECHANISMS SUCH AS
    - CORROSION EFFECTS
    - INTERFACE STABILITY
    - PHOTOTHERMAL EFFECT
  - DEVELOP LIFETIME PREDICTION METHODOLOGIES FOR PROJECTION OF REALISTIC LIFE-CYCLE COST ECONOMICS DATA NEEDED TO DEFINE COMPETITIVE PHOTOVOLTAIC SYSTEMS

Process Development

- PROCESS SEQUENCES TO DEVELOP SHEET MATERIAL INTO PHOTOVOLTAIC CELLS HAVE MANY TECHNOLOGICAL STEPS

- SURFACE PREPARATION, METALLIZATION, ANTIREFLECTIVE COATING AND JUNCTION FORMATION HAVE ALTERNATIVE APPROACHES BUT HAVE BEEN EXPENSIVE FOR COMPETIT-TIVE POWER SYSTEMS

- PROMISING WORK HAS BEEN ACCOMPLISHED IN IMPROVING INTERRELATIONSHIPS OF PROCESS STEPS AND IN REDUCING COSTS

- THE WORK REMAINING IS TO DEFINE PROCESS STEPS THAT ARE:

  - COMPATIBLE WITH DIFFERENT SHEET MATERIALS
  - CONSISTENT WITH COST-COMPETITIVE PV SYSTEMS
  - SCALABLE FROM LABORATORY EXPERIENCE BY INDUSTRY TO LEVELS OF INTEREST TO THEM

- SPECIFIC TASKS OF PRIMARY IMPORTANCE ARE:

  - OHMIC CONTACT
  - DIFFUSION BARRIER IN ADVANCED METALLIZATION SYSTEMS
  - HIGH-EFFICIENCY CELL-JUNCTION FORMATION
  - ADVANCED ANTIREFLECTIVE COATINGS

Summary

- A GREAT DEAL OF WORK REMAINS TO BE DONE

- SUFFICIENT R&D BY THE LSA PROJECT WILL BE NECESSARY TO REDUCE ADOPTION RISKS TO AN ACCEPTABLE LEVEL FOR INDUSTRY TO PROVIDE COMPETITIVE PHOTOVOLTAIC POWER

PV USERS' VIEWPOINTS ON MODULES AND ARRAYS

TRISOLAR CORP.

R. Matlin

Module Size vs Installation Cost

- RACK OR STANDOFF OR DIRECT MOUNT SYSTEMS SHOW INSTALLATION COST PROPORTIONAL TO NUMBER OF MODULES.

- INTEGRAL MOUNT SYSTEMS SHOW INSTALLATION COST PROPORTIONAL TO A COMBINATION OF NUMBER OF MODULES AND TOTAL PERIMETER OF MODULES.

- SYSTEMS OVER 1KW SHOW SIGNIFICANT COST IMPACT OF MODULE SIZE.

- IDEAL MODULE SIZE IS LIMITED TO APPROXIMATELY

  4 FT. X 6 FT.

  OR 10% OF SYSTEM TOTAL

  WHICHEVER IS SMALLER.

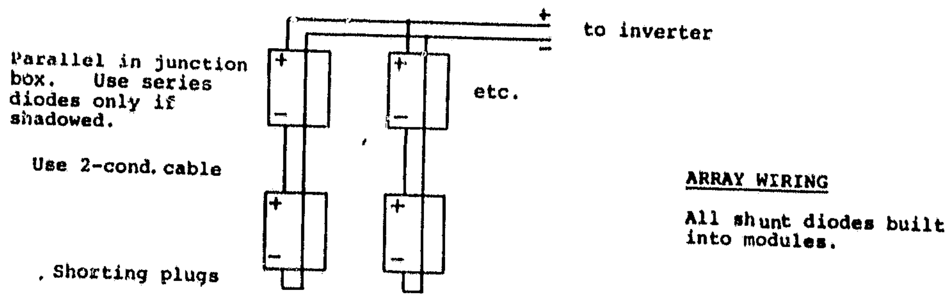
- IMPACT OF SMALL (4 FT^2) MODULES ON LARGE SYSTEM INSTALLATIONS CAN BE AS HIGH AS AN EXTRA \$1 TO \$2 PER WATT INSTALLATION COST.

- USE OF SEVERAL SMALL MODULES IN A PRE-ASSEMBLED FRAME SHIFTS COST BURDEN TO THE FACTORY. PRE-ASSEMBLED WATER-PROOF FRAMES (INTEGRAL MOUNTING) CAN BE EXPENSIVE.

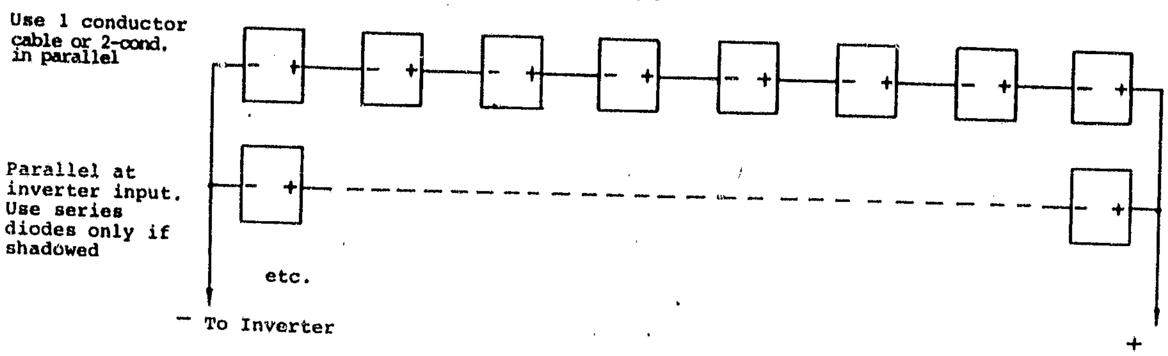
Roof-Integrated Modules: High vs Low Voltage

PARAMETER	UNITS	PANEL A	PANEL AA
C-CW spacing	in.	48	48
C-CL spacing	in.	75-½	83-½
Glass width	in.	47	47
Glass length	in.	74-½	82-½
Total area	m^2	2.34	2.50
Active area width	in.	44	44
Active area length	in.	72	80
Active area	m^2	2.04	2.27
Volt pk 28°C	V	98	27.5
45°C	V	88.9	24.9
Amps pk	A	2.50	10.0
Watts 28°C	W	245	275
45°C	W	222	249
Cell width	in.	4	4
Cell length	in.	4	4
No. cells, Shape	-	198 sq.	220 sq.
Cell series	-	196	55
Cells parallel	-	1	4
Active area effic. 28°C	%	12.0	12.0
Total area effic. 28°C	%	10.5	10.5
Total area effic. 45°C	%	9.5	9.5
No. panels per minimum string	-	2	8

Module A



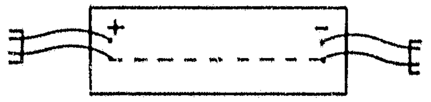
Module AA



Wiring Schemes

PANEL A, STANDOFF MOUNT

Use AMP Econo-seal circular plastic waterproof connectors, factory installed.

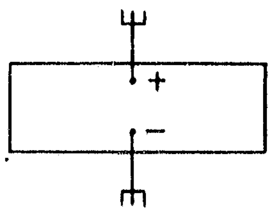


PANEL A, INTEGRAL MOUNT

Use AMP NM-1 Romex splice hermophroditic connectors, field or factory installed, same wiring diagram as above.

PANEL AA, STANDOFF MOUNT

Use AMP Photovoltaic connector, factory installed.



PANEL AA, INTEGRAL MOUNT

Use AMP NM-1 connector with all wires in parallel, field or factory installed, same wiring diagram as above.

Mismatch Losses

CELL TO CELL MISMATCH OF CURRENT ± 10% VOLTAGE MATCH BETTER.

MODULES WITH LOW LEVEL PARALLELING GIVE LOWER SYSTEM MISMATCH LOSSES.

LOW V, HIGH I	LOW I, HIGH V
LOW LEVEL PARALLELING (8) WITHIN MODULE	MANY SERIES CELLS, 2 PARALLEL WITHIN MODULE
EXAMPLE: MODULE AA, SYSTEM 2	EXAMPLE: MODULE A SYSTEM 1
SERIES MODULE WIRING	SERIES MODULE WIRING
MODULE CURRENT MISMATCH: ± 3.5%	± 7%

SIMILAR RESULT CAN BE ACHIEVED BY PARALLELING SMALL MODULES BEFORE SERIES CONNECTION.

CONCLUSION: LOW LEVEL PARALLELING PROBABLY INCREASES PERFORMANCE 3 TO 5%.

ARIZONA PUBLIC SERVICE CO.

M. Brown

History of Electric Utility Industry

1882 TO 1920'S
- EDISON ILLUMINATED CO., 100 BUILDINGS IN MANHATTAN
- MOSTLY HYDRO, SOME COAL
- COMPETITION IN SOME GEOGRAPHIC REGIONS, LOOSE REGULATION

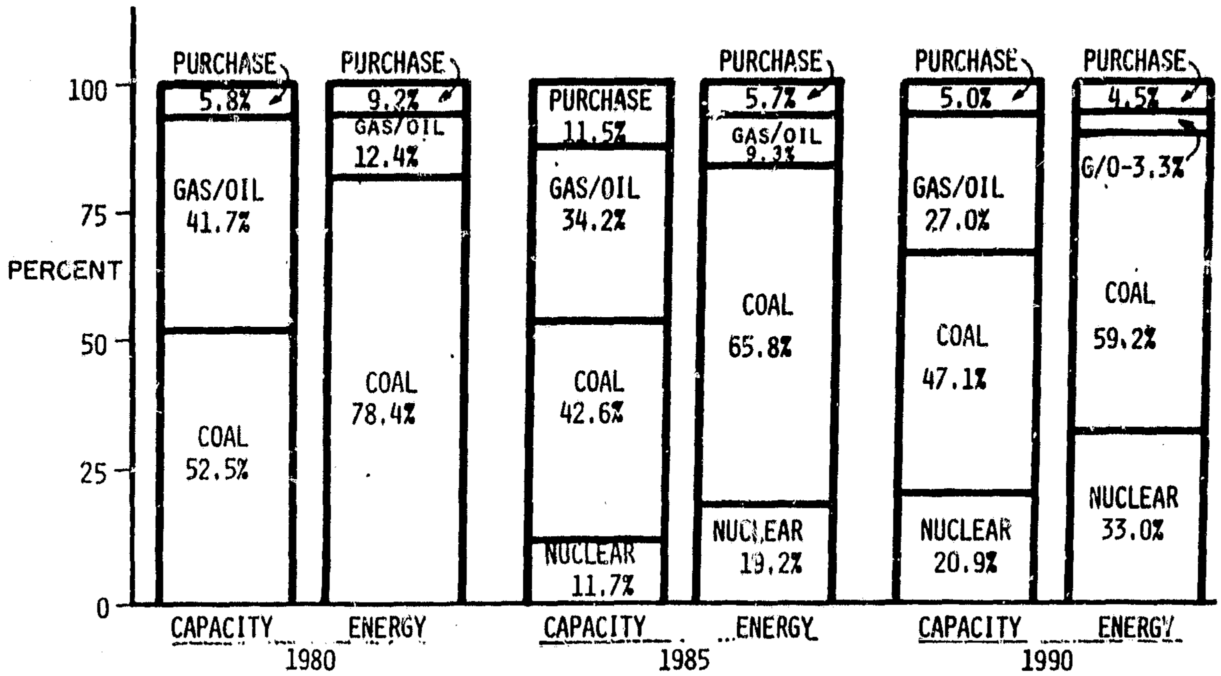
1920'S TO 1930'S
- LARGE HOLDING COMPANIES DEVELOPED TO FINANCE EXPANSION AND INTERCONNECT
- 15 TOP HOLDING COMPANIES CONTROLLED 80% OF INVESTOR OWN GENERATION

1930'S TO 1940'S
- 1935 PUBLIC UTILITY HOLDING COMPANY ACT - RESULT OF UNFAVORABLE PUBLIC OPINION TOWARDS HOLDING COMPANIES
- PUBLIC POWER PROJECTS POPULARIZED BECAUSE OF ECONOMICS OF DEPRESSION, DISENCHANTMENT WITH HOLDING COMPANIES, AND GENERAL MOOD THAT FEDERAL GOVERNMENT COULD SOLVE SOCIAL AND ECONOMIC PROBLEMS.
- PUBLIC POWER RECEIVED GOVERNMENT SUBSIDIES IN LOW-COST LOANS, NO INCOME TAXES, NOMINAL PAYMENTS FOR OTHER TAXES.

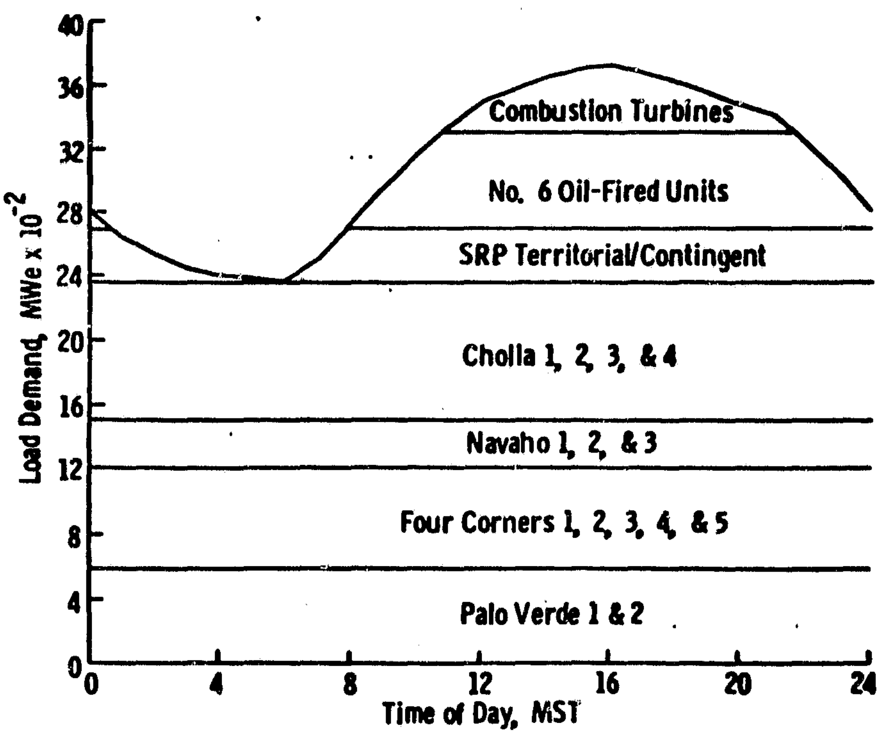
1940'S TO 1960'S
- GROWTH IN INVESTOR-OWN UTILITIES - ABOUT 100% FOR EACH DECADE
- INVESTOR-OWN UTILITIES CAME TO ACCOUNT FOR ABOUT 80% OF CAPACITY
- TECHNOLOGICAL IMPROVEMENTS, STABLE ECONOMY, AND ECONOMY OF SCALE CAUSED REDUCING UTILITY RATES.

1960'S TO 1980'S
- IMPROVEMENTS PEAKED OUT, INFLATION, AND ENVIRONMENTAL FIXES REVERSED REDUCING RATE TREND.
- DIMINISHING OIL AND NATURAL GAS SUPPLIES CAUSE SWITCH TO COAL, NUCLEAR, ETC.
- NEW PLANTS TEND TO RELATIVELY HIGHER CAPITAL COSTS.

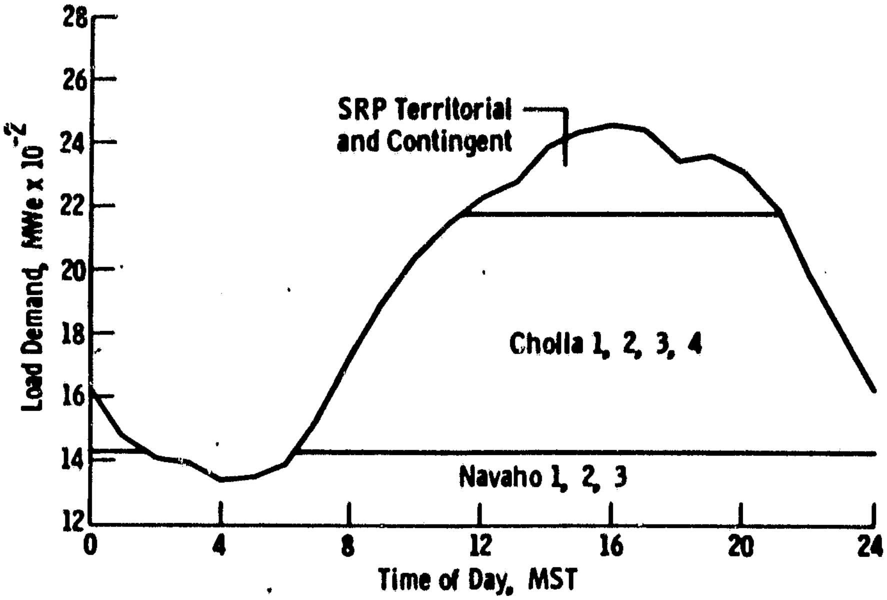
Capacity and Energy Mix by Fuel Type (APS)



Peak Demand Day Load Demand: Aug. 23, 1985



Fall Day Load Demand: 1985



Utility Requirements of a Generating Plant

VITAL REQUIREMENTS

"MUST":

- O WORK
- O BE ECONOMICALLY COMPETITIVE*
- O BE LICENSABLE+
- O HAVE ESTABLISHED SUPPLIER BASE*
- O BE ACCEPTABLY SAFE*
- O BE OPERABLE*
- O BE GENERALLY ACCEPTABLE TO PUBLIC+
- O ACCEPTABLY INTERFACE WITH GRID*

FLEXIBLE REQUIREMENTS

"MINIMIZE":

- O CAPITAL*, O&M*, AND FUEL COSTS+
- O PLANT CONSTRUCTION TIME+
- O STARTUP POWER REQUIREMENTS+
- O WASTE PROBLEMS+
- O LAND REQUIREMENTS*
- O DECOMMISSIONING EFFORT
- O STARTUP TIME+
- O LOWEST OPERATING LEVEL+
- O ENVIRONMENTAL IMPACTS AND HAZARDS

"MAXIMIZE":

- O AVAILABILITY*
- O FLEXIBILITY IN UNIT RATING+
- O CAPACITY CREDIT*
- O PLANT LIFE*+
- O EFFICIENCY*
- O PART-LOAD EFFICIENCY
- O LOAD FOLLOWING CAPABILITY*
- O SITING FLEXIBILITY

* MAY BE OF SPECIAL CONCERN IN THE CASE OF PHOTOVOLTAICS.

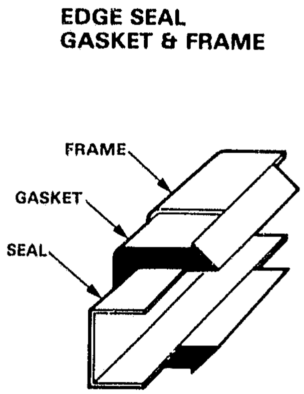
\+ PHOTOVOLTAICS <u>MAY</u> HAVE SIGNIFICANT COMPETITIVE ADVANTAGE.

PHOTOVOLTAIC COLLECTOR RELIABILITY: DOE EXPERIENCE

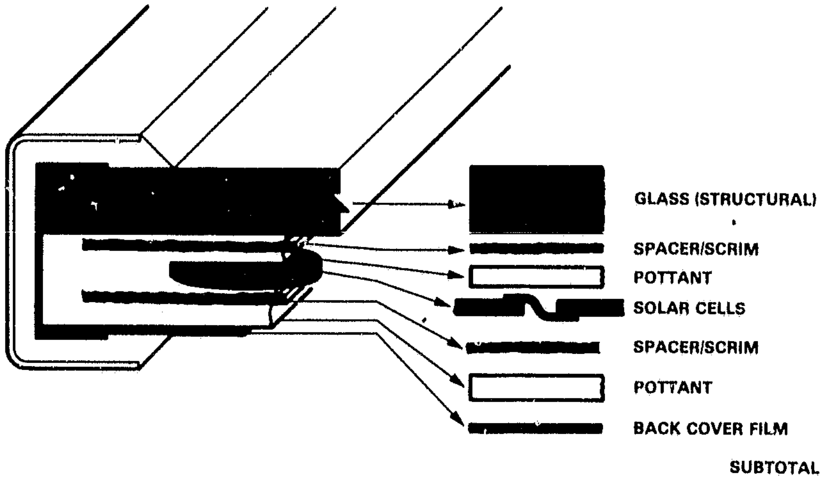
JET PROPULSION LABORATORY

J.A. Evans

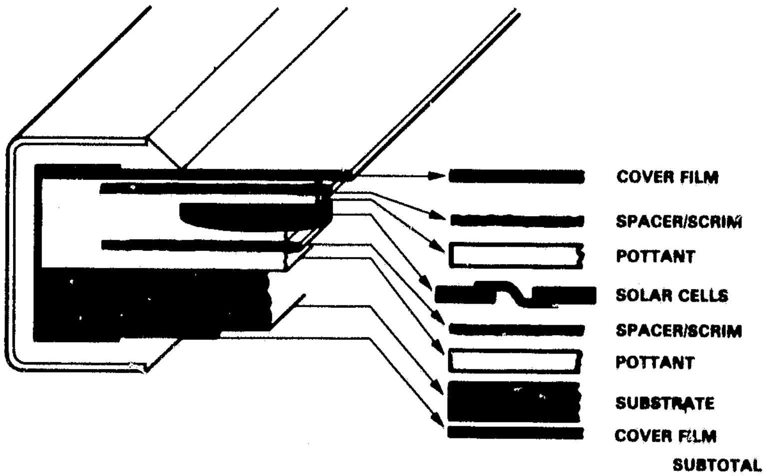
Encapsulation Concepts



SUPERSTRATE DESIGN



SUBSTRATE DESIGN



Large-Scale Module Procurements

	MANUFACTURERS	QUANTITY (kW)	TECHNOLOGY	PROD. COMPLETE	FIELD EXPERIENCE (YEARS)
I	4	58	1975	1976	2-4
II	4	110	1975	1978	$1\frac{1}{2}$-4
III	5	216	1976	1980	1-$2\frac{1}{2}$
IV	8	28	1978	1981	0
V	7*		1981		

* SEVEN SELECTED FOR NEGOTIATION

	WATTS	CELLS	MANUFAC-TURERS	HOW CONNECTED	MULTIPLE INTERCONNECTS	SUBSTRATE	ENCAPSU-LANTS	SUPERSTRATE
I	5-15	18-25	4	SERIES	NO	Aℓ OR EPOXY F.G.	SILICONE	GLASS(1)
II	10-30	40-120	4	SERIES (PARALLEL) (1)	YES	Aℓ OR POLYESTER F.G.	SILICONE PVB (1)	GLASS(1)
III	10-35	40-48	5	SERIES (PARALLEL) (1)	YES	STEEL, Aℓ OR POLYESTER F.G.	SILICONE PVB (1)	GLASS(2)
IV	18-85	19-108	8	SERIES (PARALLEL) (7)	YES	STEEL (1) ACRYLIC (1)	EVA (5) PVB (4) RTV (1)	GLASS(8)

Qualification Tests for Flat-Plate Modules

TESTS	MODULES BLK I	BLK II	BLK III	BLK IV
THERMAL CYCLE	X	X	X	X
HUMIDITY CYCLE	X	X	X	X
MECHANICAL LOADING		X	X	X
WIND RESISTANCE				X
TWIST		X	X	X
HAIL IMPACT				X
ELECTRICAL ISOLATION		X	X	X
GROUND CONTINUITY			X	X

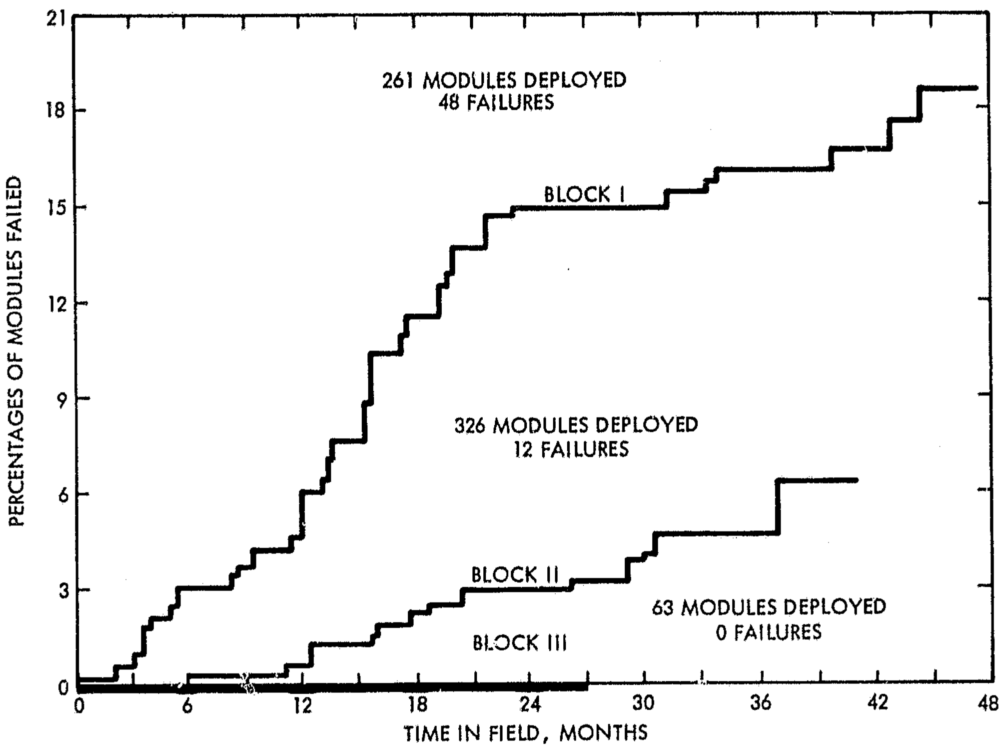
Module Durability Experience: Block Buy Module Utilization (kW)

	I	II	III
APPLICATIONS EXPERIMENTS			
• NASA LeRC			
SCHUCHULI INDIAN VILLAGE		3.5	
UPPER VOLTA VILLAGE (GSA BUY)		1.8	
REMOTE STAND-ALONE	1.6	0.5	0.4
• MIT/LL			
NATURAL BRIDGES, UTAH		20	80
MEAD, NEBRASKA		28	
BRYAN, OHIO		15	
RESIDENTIAL			14
CHICAGO MUSEUM	1.5		
• DOD			
MOUNT LAGUNA, CALIFORNIA		7	53
MILITARY APPLICATIONS	12		
FIELD TEST SITES			
• NASA LeRC	13		20
• MIT/LL	5	4	
• JPL		6.2	1.1
• SANDIA		4	

JPL Test Sites

CATEGORY	LOCATION	LATITUDE (degrees)	ALTITUDE (feet)	KEY FEATURES
EXTREME WEATHER	CANAL ZONE (FT. CLAYTON)	9	~0	TYPICAL TROPIC: HOT AND HUMID; 100 INCH PER YEAR RAINFALL
	ALASKA (FT. GREELY)	64	1,270	SEMI-ARCTIC: DRY, COLD AND WINDY: -30°F WINTERS
MARINE	POINT VICENTE, CA	34	~0	COOL DAMP MORNINGS AND CLEAR AFTERNOONS; CORROSIVE SALT SPRAY
	KEY WEST, FLA.	25	~0	HOT AND HUMID; CORROSIVE SALT SPRAY
	SAN NICHOLAS ISLAND, CA	34	~0	SOMEWHAT MILDER THAN KEY WEST
MOUNTAIN	TABLE MOUNTAIN, CA	34	7,500	TYPICAL ALPINE ENVIRONMENT: HEAVY WINTER SNOWS AND MILD SUMMERS; HIGH VELOCITY [illegible]
	MINES PEAK, CO	40	13,000	CLEAR AND COLD; HIGH VELOCITY WINDS, MA- [illegible]
HIGH DESERT	GOLDSTONE, CA	35	3,400	VERY HOT AND DRY SUMMERS; CLEAR SKIES
	ALBUQUERQUE, NM	35	5,200	DRY WITH CLEAR SKIES; AN ABUNDANCE OF [illegible]
	DUGWAY, UTAH	40	4,300	COLD WINTERS, HOT SUMMERS; ALKALINE SOIL
MIDWEST	CRANE, INDIANA	39	~0	TYPICAL MIDWEST: HOT HUMID SUMMERS, COLD SNOWY WINTERS
NORTHWEST	SEATTLE (FT. LEWIS)	47	~0	TYPICAL NORTHWEST; MILD TEMPERATURES AND AN ABUNDANCE OF RAIN
UPPER GREAT LAKES	HOUGHTON, MICHIGAN	47	750	MILD SUMMERS, SEVERE WINTERS
URBAN SOUTHERN CALIFORNIA	JPL/PASADENA	34	1,250	PRIMARY TEST SITE - HOT SUMMERS AND MILD WINTERS; VERY HIGH POLLUTION ENVIRONMENT
URBAN COASTAL	NEW LONDON, CONNECTICUT	41	~0	TYPICAL NEW ENGLAND COASTAL
	NEW ORLEANS, LOUISIANA	30	~0	HOT AND VERY HUMID; HIGH POLLUTION ENVIRONMENT

Failure* Rates at LSA Field Test Sites

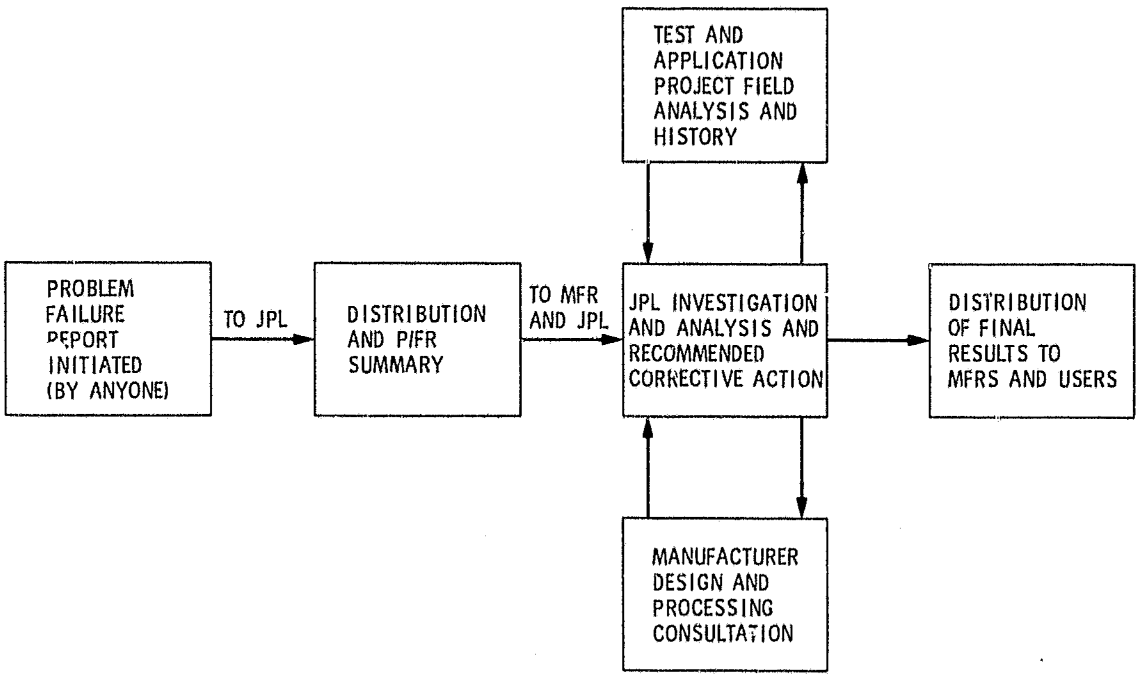


*FAILURE - OUTPOWER DECREASE GREATER THEN 25%

Modules Now Under Test

CATEGORY	LOCATION	BLOCK I NUMBER	BLOCK I DEPLOYED	BLOCK II NUMBER	BLOCK II DEPLOYED	BLOCK III NUMBER	BLOCK III DEPLOYED
EXTREME WEATHER	CANAL ZONE (FT CLAYTON)			16	12/77		
	ALASKA (FT GREELY)			16	10/77		
MARINE	POINT VICENTE, CA			18	8/78	15	11/78
	KEY WEST, FLA			14	12/77		
	SAN NICHOLAS ISLAND, CA			12	4/78		
MOUNTAIN	TABLE MOUNTAIN, CA	39	11/76-3/77	18	4/77-11/77	15	11/78
	MINES PEAK, CO			0	(5/78)		
HIGH DESERT	GOLDSTONE, CA	44	12/76-4/77	18	4/77-9/77	15	1/79
	ALBUQUERQUE, NM			16	2/78		
	DUGWAY, UTAH			16	1/78		
MIDWEST	CRANE, INDIANA			16	12/77		
NORTHWEST	SEATTLE (FT LEWIS)			16	1/78		
UPPER GREAT LAKES	HOUGHTON, MICHIGAN			15	11/77		
URBAN SOUTHERN CALIFORNIA	JPL, PASADENA	129	10/76-3/77	73	12/76-11/77	18	10/78-2/79
URBAN COASTAL	NEW LONDON, CONNECTICUT			16	1/78		
	NEW ORLEANS, LOUISIANA			14	2/78		

Problem-Failure Report (P/FR) Flow Plan



Field Reliability Data Base

- SOURCES
  - LeRC
  - MIT/LL
  - JPL
- TYPES
  - MODULE FAILURE RATES
  - MODULE/ARRAY ELECTRICAL DEGRADATION
  - PHYSICAL OBSERVATIONS
- DATA CAVEATS
  - DIFFERING SOURCES & TECHNIQUES
  - VARIABLE FREQUENCY & RIGOR
  - OBSERVATIONAL DIFFICULTIES

Application Experiments Module Failures

FIELD CENTER	INSTALLATION	# OF MODULES	# OF FAILURES	% MODULES FAILED	OPERATING TIME (YEARS)
NASA LeRC	SCHUCHULI, AZ	192	34	17.7	2
	UPPER VOLTA	100	26	26.0	1 1/2
	ALL OTHERS	314	13	3.8	2-4
MIT/LL	NATURAL BRIDGES, UT	4524	29	0.6	1/2
	MEAD, NE	2240	66	2.9	3
	U. OF TEXAS, ARL.	240	65	27.1	1 1/2
	ALL OTHERS	4113	55	1.3	1/2 - 3
SANDIA (JPL)	MT. LAGUNA, CA	2366	179	7.6	1
TOTAL		14,089	467	3.3	

Field Test and Applications P/FR Summary

BLOCK	INTERCONNECT FRACTURES	UNSOLDERED INTERCONNECTS	CRACKED CELLS	WIRE AND TERMINAL CORROSION	GROUNDED CELL STRING	EXPOSED INTERCONNECTS	ENCAPSULANT DELAMINATION
I	24	11	22	9	2	4	27
II	26	15	71	7	18	4	29
III	14	4	24	5	11	0	21
TOTAL	18%	9%	34%	6%	9%	2%	22%

Key Failure Modes and Mechanisms

- ELECTRICAL INTERCONNECT BREAKAGE
  - THERMAL CYCLING
- SOLAR CELL CRACKING
  - THERMAL CYCLING
  - HAIL IMPACT
  - REVERSE VOLTAGE BIAS HEATING
- ENCAPSULANT DELAMINATION AND CRACKING
  - THERMAL CYCLING
  - HUMIDITY
  - ULTRAVIOLET RADIATION
- CORROSION (CELL METALLIZATION, WIRE, TERMINAL)
  - HUMIDITY
  - CONTAMINANTS
- ELECTRICAL INSULATION BREAKDOWN
- OPTICAL SURFACE SOILING

Failure Mode: Interconnect Fracture

• PERCENTAGE OF P/FR's:	18%
• NUMBER OF MANUFACTURERS INVOLVED:	4
• CAUSE:	FATIGUE FAILURE, PRIMARILY INDUCED BY DIFFERENTIAL THERMAL EXPANSION STRESSES DURING DIURNAL TEMPERATURE CYCLING
• EFFECT:	INTERMITTENT TO CONTINUOUS OPEN CIRCUIT, SOMETIMES ACCOMPANIED BY ARCING ACROSS FRACTURE
• NOTABLE EXAMPLES:	BLOCK II POLYESTER SUBSTRATE MODULES AT UPPER VOLTA AND SCHUCHULI

Failure Mode: Environmental-Stress-Cracked Cells

• PERCENTAGE OF P/FR's:	25%
• NUMBER OF MANUFACTURERS:	4
• CAUSE:	MAINLY HAIL AND DIFFERENTIAL THERMAL EXPANSION STRESS ON CELLS DAMAGED IN MANUFACTURE
• EFFECT:	2-4% OF VISIBLY CRACKED CELLS HAVE LED TO OPEN CIRCUIT IN FIELD
• NOTABLE EXAMPLES:	HAIL DAMAGE EXISTS AT MOST SITES WITH BLOCK I-III MODULES

Failure Mode: Reverse-Bias-Cracked Cells

● PERCENTAGE OF P/FR's:	9%
● NUMBER OF MANUFACTURERS:	2
● CAUSE:	CELL HEATING FROM REVERSE VOLTAGE BIAS GAS GENERATION UNDER CELL CRACKED CELL OPEN/SHORTED CELL
● EFFECT:	POWER DEGRADATION OR LOSS
● NOTABLE EXAMPLES:	MOUNT LAGUNA

Degradation Mode: Encapsulation Delamination

● PERCENTAGE OF P/FR's:	22%
● NUMBER OF MANUFACTURERS:	4
● CAUSE:	SILICONE RUBBER TO SUBSTRATE ADHESIVE BOND FAILURES UNDER MOISTURE, THERMAL, UV, AND WIND STRESSES
● EFFECT:	EXPOSURE OF CELLS AND INTERCONNECTS; MOISTURE ENTRAPMENT. NO IMMEDIATE FUNCTIONAL EFFECT
● NOTABLE EXAMPLES:	MOST INSTALLATIONS

Failure Mode: Grounded Cell String

- PERCENTAGE OF P/FR's: 9%
- NUMBER OF MANUFACTURERS: 4
- CAUSE: DESIGN/WORKMANSHIP
- EFFECT: POWER LOSS; POTENTIAL FOR ARCING; MAINTENANCE PROBLEM
- NOTABLE EXAMPLES: NATURAL BRIDGES

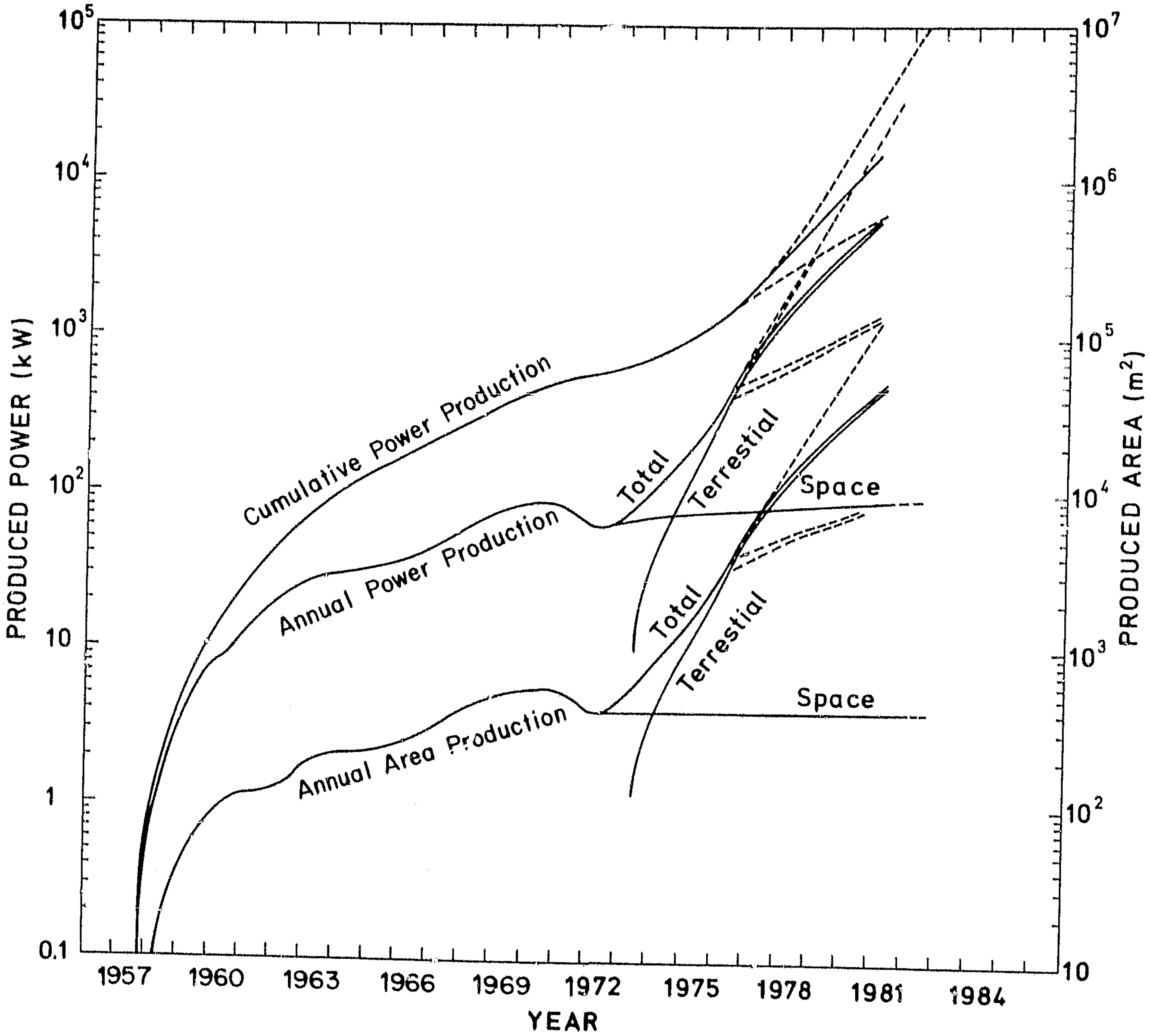
Conclusions

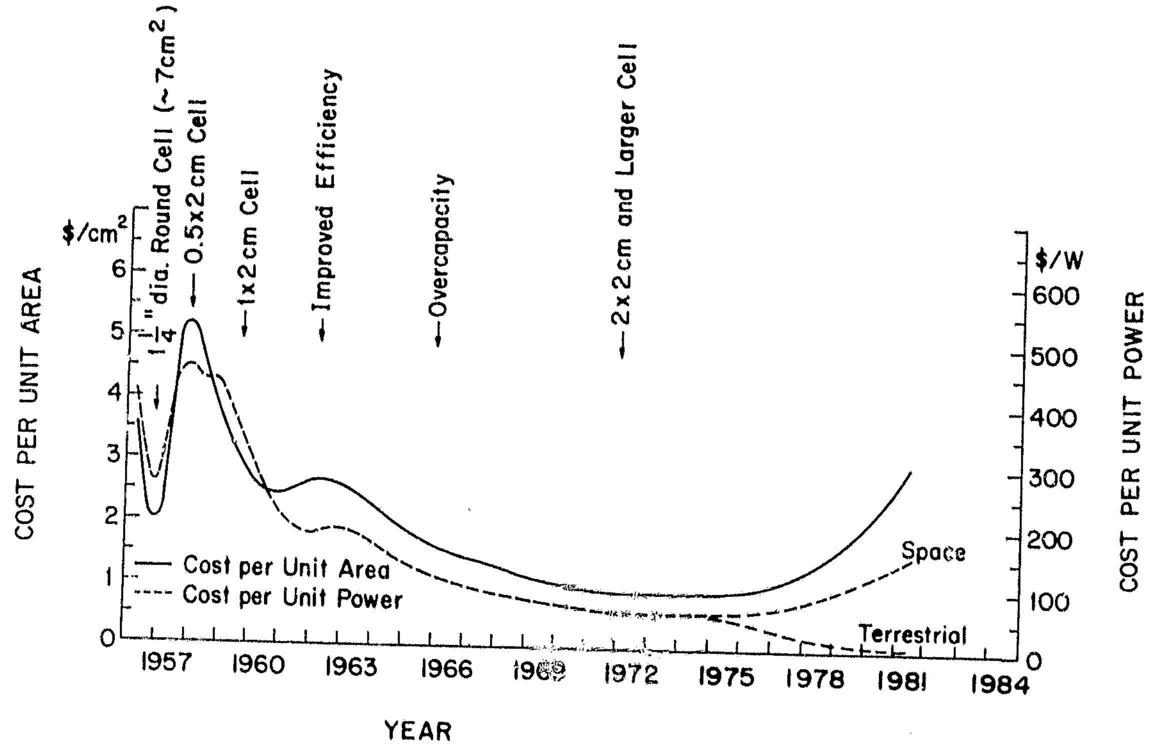
- FAILURE MECHANISMS ARE COMPLEX
- POOR PREDICTION CAPABILITY PLACES HIGH RELIANCE ON QUALIFICATION TESTS AND SYSTEM EXPERIMENTS
- LESSONS
  - IMPORTANCE OF MATERIAL CHOICES REEMPHASIZED
  - INTERCONNECT DESIGN
    REDUNDANCY, CONFIGURATION
  - HAIL PROTECTION
  - REVERSE BIAS PROTECTION
  - INCREASE DESIGN MARGINS
  - EMPHASIS ON QA/QC

FUTURE TECHNOLOGY NEEDS

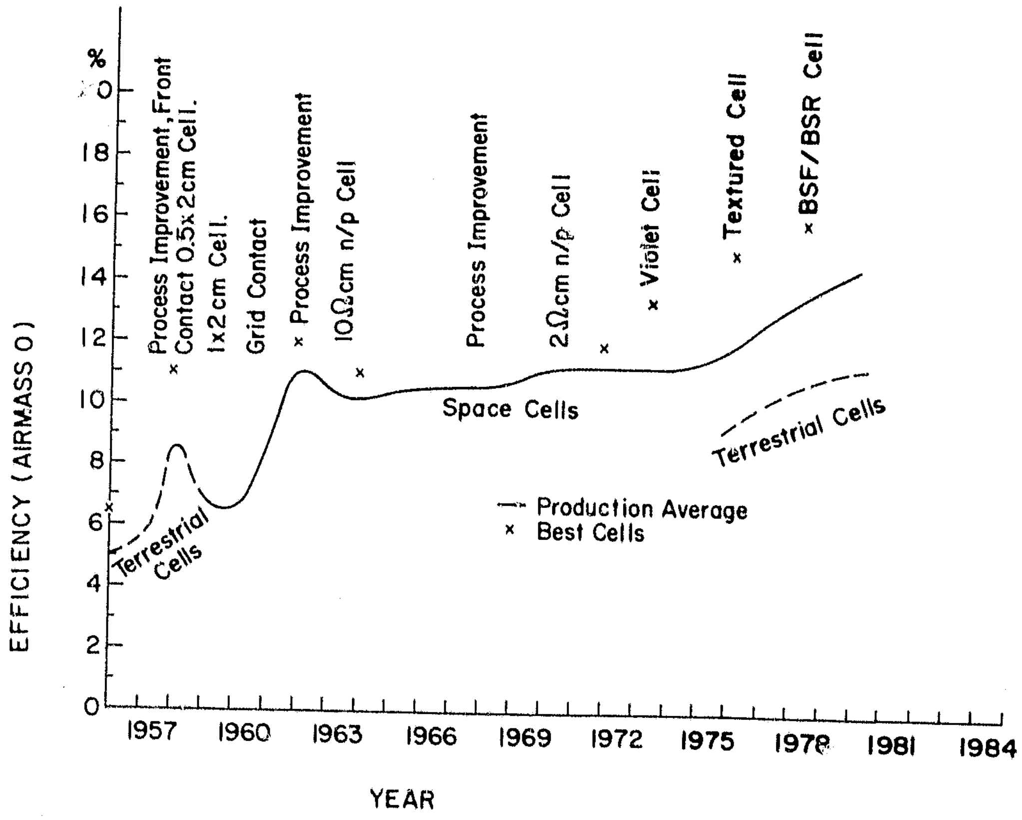
UNIVERSITY OF PENNSYLVANIA

M. Wolf





COST PER UNIT AREA
$/cm²
1 1/4" dia. Round Cell (~7cm²)
0.5x2cm Cell
1x2cm Cell
Improved Efficiency
Overcapacity
2x2cm and Larger Cell
$/W
COST PER UNIT POWER
Cost per Unit Area
Cost per Unit Power
Space
Terrestrial
1957 1960 1963 1966 1969 1972 1975 1978 1981 1984
YEAR



EFFICIENCY (AIRMASS 0)
%
Process Improvement, Front Contact 0.5x2cm Cell.
1x2cm Cell.
Grid Contact
Process Improvement
10Ωcm n/p Cell
Process Improvement
2Ωcm n/p Cell
Violet Cell
Textured Cell
BSF/BSR Cell
Space Cells
Terrestrial Cells
Terrestrial Cells
Production Average
Best Cells
1957 1960 1963 1966 1969 1972 1975 1978 1981 1984
YEAR

What Have We Learned?

I. THE SOLAR CELL IS A HIGHLY SOPHISTICATED DEVICE, PRODUCED IN A PROCESS WITH MANY SEQUENTIAL STEPS.

II. ITS DESIGN AND ITS PRODUCTION HAVE REACHED A HIGH TECHNOLOGY LEVEL, BUT THERE IS GREAT POTENTIAL FOR FUTURE TECHNOLOGY ADVANCES, IN A MULTITUDE OF APPROACHES.

III. THE PRESENT LEVEL OF TECHNOLOGY HAS BEEN REACHED THROUGH A LARGE NUMBER OF RELATIVELY SMALL ADVANCES, USUALLY BUILDING ON EACH OTHER. SUCCESSFUL "BREAKTHROUGHS" ARE HARD TO FIND.

IV. IN DEVICE DESIGN AND IN PROCESS METHODS, THE EARLY PROGRESS HAS GENERALLY BEEN EMPIRICAL, FOLLOWED BY SUCCESSIVELY DEEPENED UNDERSTANDING OF THE UNDERLYING PRINCIPLES, AND BY TECHNOLOGY ADVANCES BASED ON THIS UNDERSTANDING.

THIS PROGRESS HAS INVOLVED SIGNIFICANT R&D BY DIVERSE CONTRIBUTORS. A SUBSTANTIAL PART OF THE ADVANCES HAS BEEN BASED ON NEW FINDINGS MADE OUTSIDE OF THE FIELD.

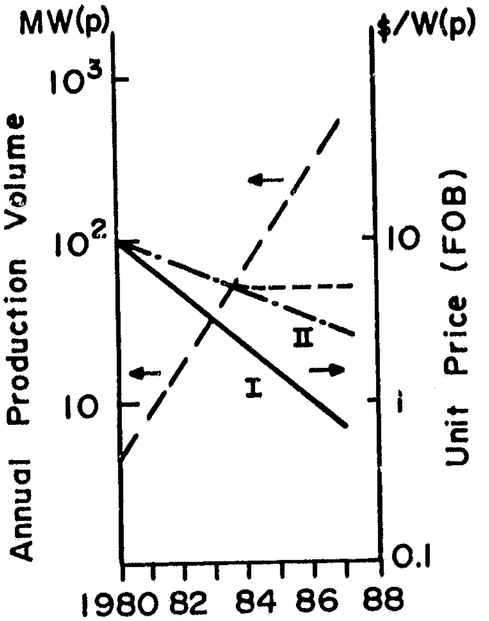
EXAMPLE 1: "FIELD-FREE" SOLAR CELL → CELL WITH FIELD THROUGHOUT BASE REGION → CELL WITH FIELD NEAR BACK CONTACT (BSF CELL) → CELL WITH HIGH-LOW JUNCTION NEAR BACK CONTACT → CELL WITH HIGH-LOW JUNCTION AND "THICK" THIRD LAYER NEAR CONTACT.

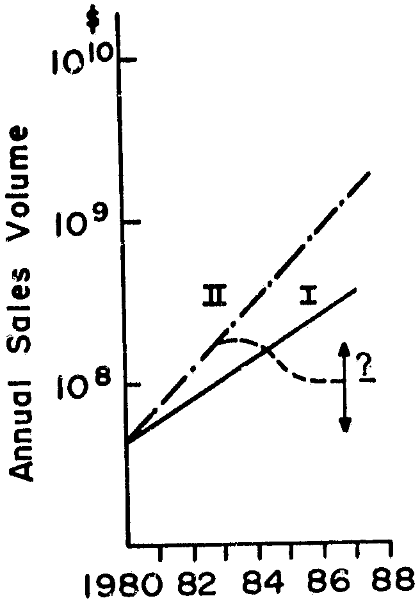
EXAMPLE 2: CZOCHRALSKI CRYSTAL GROWING:

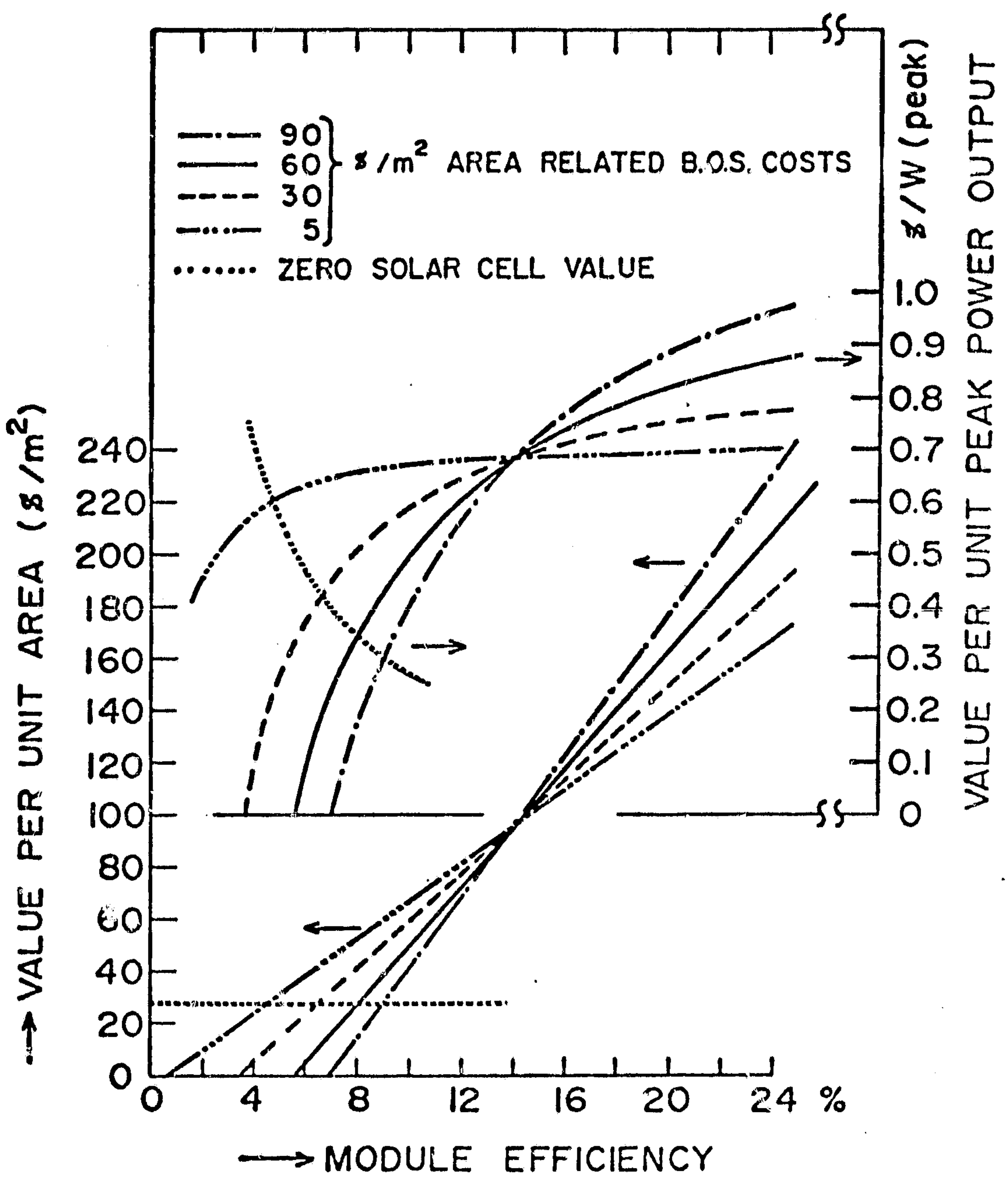
1956: 150G INGOTS ~ 3/4" DIAMETER, 1 QUARTZ CRUCIBLE PER INGOT, COMPLETELY MANUAL CONTROL, 1 OPERATOR/FURNACE.

GRADUAL TECHNOLOGY ADVANCEMENT TO:

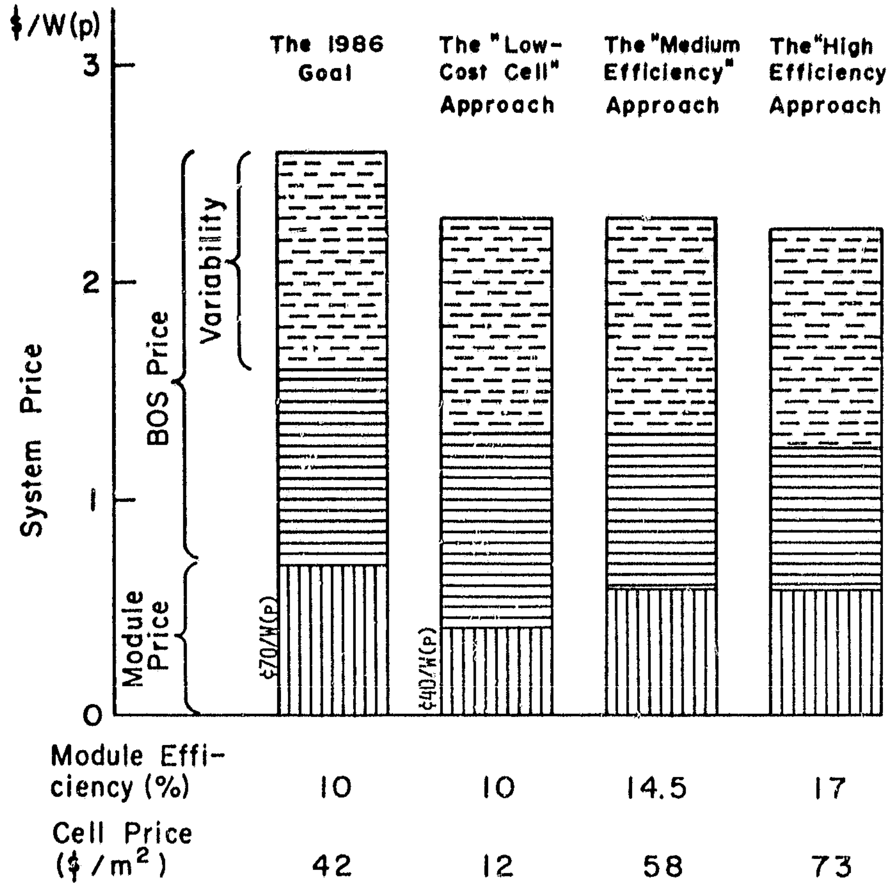
1981: 150KG PER QUARTZ CURCIBLE, 6" DIAMETER INGOTS, FULLY AUTOMATIC GROWTH CONTROL, 1 OPERATOR FOR 3-4 FURNACES.


MW(p)
$/W(p)
Annual Production Volume
Unit Price (FOB)
10³
10²
10
10
1
0.1
II
I
1980 82 84 86 88


$
10¹⁰
10⁹
10⁸
Annual Sales Volume
II
I
?
1980 82 84 86 88



90
60
30
5
$/m² AREA RELATED B.O.S. COSTS
ZERO SOLAR CELL VALUE
$/W (peak)
VALUE PER UNIT PEAK POWER OUTPUT
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
VALUE PER UNIT AREA ($/m²)
240
220
200
180
160
140
120
100
80
60
40
20
0
0
4
8
12
16
20
24 %
MODULE EFFICIENCY



ASSUMPTION: AREA-RELATED BOS COST \$60/M^2. ENCAPS'N AND MOD. ASS'Y: \$28/M^2.

The Four Areas Needing Technology Progress

1.	INCREASED EFFICIENCY	- CELL/MODULE/SYSTEM LEVEL
2.	ADVANCED PROCESS TECHNOLOGIES	- RANGE FROM RESOURCE TO PRODUCT - COST REDUCTION COMMENSURATE WITH EFFICIENCY GOALS - SELECTION CONSIDERING RESOURCE LIMITATIONS
3.	INCREASED RELIABILITY	- LOWER ENERGY COST THROUGH REDUCED MAINTENANCE, EXTENDED SYSTEM LIFE
4.	MORE COST-EFFECTIVE BALANCE-OF-SYSTEM (BOS) TECHNOLOGY	- INSTALLATION - POWER CONDITIONING - ENERGY STORAGE

How to Get Higher Efficiency in Si Solar Cells

GOAL: HIGHER VOLTAGES SIMULTANEOUS WITH THE BEST CURRENTS ALREADY ACHIEVED. (V_{OC} APPROACHING 0.7V RECENTLY REPORTED.)

DESIGN:
- "NARROW" BASE AND FRONT LAYER STRUCTURES.
- HIGH-LOW JUNCTIONS.
- "WIDE" THIRD BASE LAYERS.
- OPTICAL BACK SURFACE REFLECTION.
- FRONT SURFACE TREATMENT (MIS ?).
- NO HEAVY DOPING ($> \sim 10^{18}$ CM^{-3}) IN ACTIVE LAYERS.
- RELATIVELY LONG DIFFUSION LENGTHS IN ALL ACTIVE LAYERS.
- LOW SERIES RESISTANCE.
- CAREFUL RESISTIVITY/DIFFUSION LENGTH/LAYER THICKNESS TRADE-OFFS.
- HIGHLY EFFECTIVE AR TREATMENT (TEXTURE OR 2-LAYER AR).
- METALLIZATION WITH MINIMUM SHADING.

CONSTRUCTION: HIGHLY CONTROLLED PROCESS TO ATTAIN ALL DESIGN PARAMETERS WITHIN GIVEN TOLERANCES, WHILE ACHIEVING HIGH YIELD.

NOTE: DESIGN AND CONSTRUCTION NEED TO BE OPTIMIZED FOR ALL PARAMETERS. ONE FLAW CAN LIMIT PERFORMANCE, OVERRIDING ALL OTHER EFFORTS AT PERFORMANCE GAIN.

Increased Module-System Efficiency

- HIGHER PACKING FACTORS
- HIGHER COVER TRANSMISSION
- LESS WIRING LOSS
- HIGHER POWER CONDITIONING EFFICIENCY
- BETTER STORAGE SUBSYSTEMS, ESPECIALLY HIGHER EFFICIENCY, LONGER LIFE.

Two Schools of Thought

PREMISES:	HIGH PERFORMANCE HAS A HIGH ECONOMIC VALUE. IT REQUIRES A HIGHLY PERFECT DEVICE STRUCTURE, DOWN TO THE ATOMIC LEVEL. LOW-COST APPROACHES WILL BE FOUND FOR PROCESSES WHICH YIELD HIGH PERFORMANCE.	LOW-COST MATERIALS AND PROCESSES ARE MORE IMPORTANT THAN HIGHER PERFORMANCE.
CONSEQUENCES:	ELIMINATE POTENTIALLY DAMAGING IMPURITIES AVOID CRYSTAL DEFECTS, INCLUDING DISLOCATIONS, GRAIN BOUNDARIES, ETC. CONSTRUCT DEVICE ACCORDING TO HIGH PERFORMANCE DESIGN ENHANCE COMPETITIVENESS BY HIGH RELIABILITY, LONG LIFE	SELECT LOW-COST MATERIALS, EVEN OF INADEQUATE PURITY USE LOW-COST DEPOSITION PROCESSES, LEADING TO (FINE)-POLYCRYSTALLINE OR AMORPHOUS SEMICONDUCTORS. APPLY LOW-COST DEVICE MANUFACTURING PROCESSES, EVEN IF THEY YIELD REDUCED PERFORMANCE LONG LIFE LESS IMPORTANT THAN CHEAP REPLACEMENT
APPROACH:	USE HIGH-PURITY SEMICONDUCTOR USE SINGLE CRYSTAL OR SEMI-CRYSTAL MATERIAL PROCESS TO MAINTAIN (ENHANCE?) PROPERTIES OF SEMICONDUCTOR (ANNEAL, GETTER) APPLY LOW-LOSS PROCESSES ("BSF", FINE LINE METALLIZATION, HIGH PERFORMANCE AR) CLOSELY CONTROL PROCESS TO ACHIEVE HIGH YIELD PLACE LARGE EMPHASIS ON PROCESS COST REDUCTION WHILE MAINTAINING ABOVE ATTRIBUTES	REDUCE DAMAGING IMPURITIES BY "UPGRADING" (LEACHING, REMELTING, ETC.) IMPROVE CRYSTAL STRUCTURE BY POST-TREATMENTS (HEATING, RE-MELTING, ETC.) PASSIVATE CRYSTAL DEFECTS, INCL. BOUNDARIES (ETCHING, JUNCTION FORMATION, ETC.) SET STANDARDS LOW TO GET HIGH YIELD

To Concentrate, or Not to Concentrate?

PV SYSTEMS WITH OPTICAL CONCENTRATION

- GIVE MORE OUTPUT THAN FLAT-PLATE SYSTEMS (SAME AREA) IN ARID CLIMATES
- CAN UTILIZE EXPENSIVE VERY HIGH EFFICIENCY PV CONVERTERS
- CAN DELIVER HEAT BESIDES ELECTRICITY - AT A COST
- MAY OPERATE MORE SATISFACTORILY IN ATTENDED OPERATION (CENTRAL STATION)

CONSEQUENTLY

- THERE SHOULD BE A SIGNIFICANT SPECIALTY MARKET FOR CONCENTRATOR - PV SYSTEMS
- THE GENERAL MARKET MAY BE FLAT-PLATE PV SYSTEMS

Approach to Cost Reduction

- Reduce Number of Process Steps
- Reduce Number of Pieces Handled
- Design Simplified Device Structure
- Develop Continuous Flow Process (not Batch)
- Select High Speed Processes
- Slow Process Steps Have to be Simple, (e.g., Heat Treating)
- Reduce Use of Indirect Materials
- Simplify Process:
  - Eliminate Masking
  - Eliminate Wet Processes
  - Eliminate Critical Tolerances
  - Select Processes for Compatibility
- Select Processes for High Controllability and High Yield
- Integrate Array Assembly with Device Fabrication
- Reduce Energy Use

Example: Si Slicing

Technology in Use:	∿ 40 years.
Experience:	Tremendous advancement, can slice 15 cm dia., up to 25 wafers/cm, up to 50 cm^2/min
Problems:	Work damage to wafers, blade life, (slurry usage)
Status:	Essentially empirical, do not understand cutting process.
Need:	Research into interaction of cutting tool (abrasive particle) and Si. Is ductile cutting possible? Role of lubricants? How is work damage caused, how can it be reduced?
Potential Result:	Order of magnitude increase in cutting speed

Example: Si Ribbon Growing

TECHNOLOGY IN DEVELOPMENT: ~ 20 YEARS

EXPERIENCE: WIDTH UP TO 15 CM; THICKNESS AS LOW AS 50 μM. GROWTH SPEED UP TO ~ 4 CM/MIN.

PROBLEMS: STRESSES, CRYSTAL DEFECTS, LIMITED DIFFUSION LENGTH, LIMITED GROWTH SPEED (WEB-DENDRITE POSSIBLY EXCLUDED)

NEED: RESEARCH TO UNDERSTAND THERMAL ENVIRONMENT AT GROWTH ZONE AND IN COOL-DOWN REGION, AND ITS RELATION TO STRESSES IN RIBBON, DEFECT GENERATION, AND LIMITATION OF GROWTH SPEED. HOW CAN THIS THERMAL ENVIRONMENT BE IMPROVED? WHAT ARE THE LIMITS?

POTENTIAL RESULT: HIGH QUALITY RIBBONS. INCREASED GROWTH SPEED?

Example: Electroless Plating (Ni)

TECHNOLOGY IN USE: MANY DECADES IN METAL PLATING

~ 25 YEARS INTERMITTENT IN SI CONTACT FORMATION

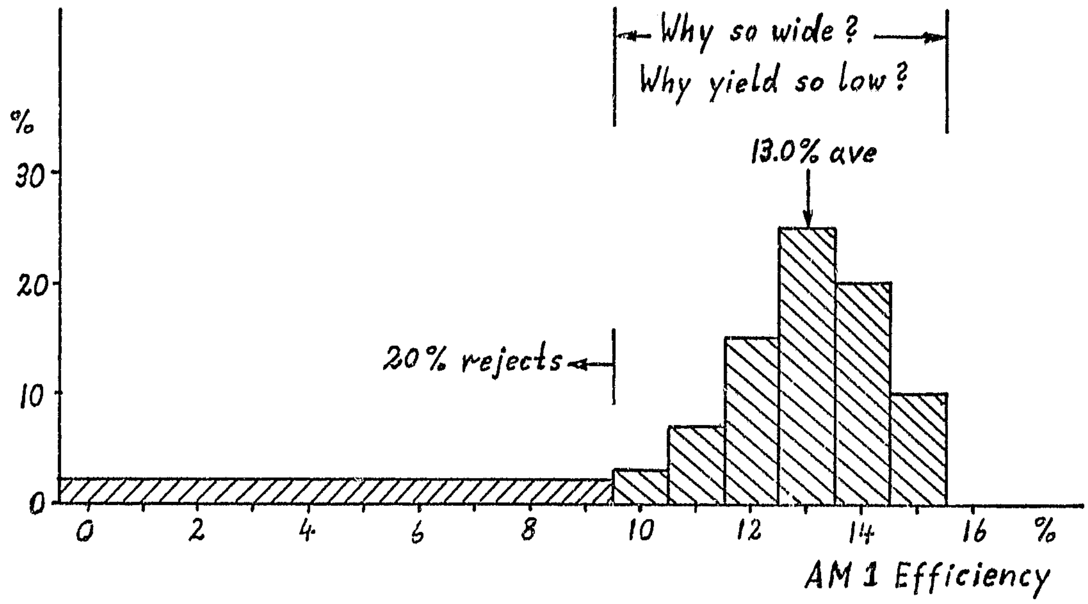
EXPERIENCE: GOOD CONTACTS CAN BE FORMED

PROBLEMS: PROCESS NOT RELIABLE, CONTACT DEGRADATION AND METAL SEPARATION INTERMITTENTLY EXPERIENCED.

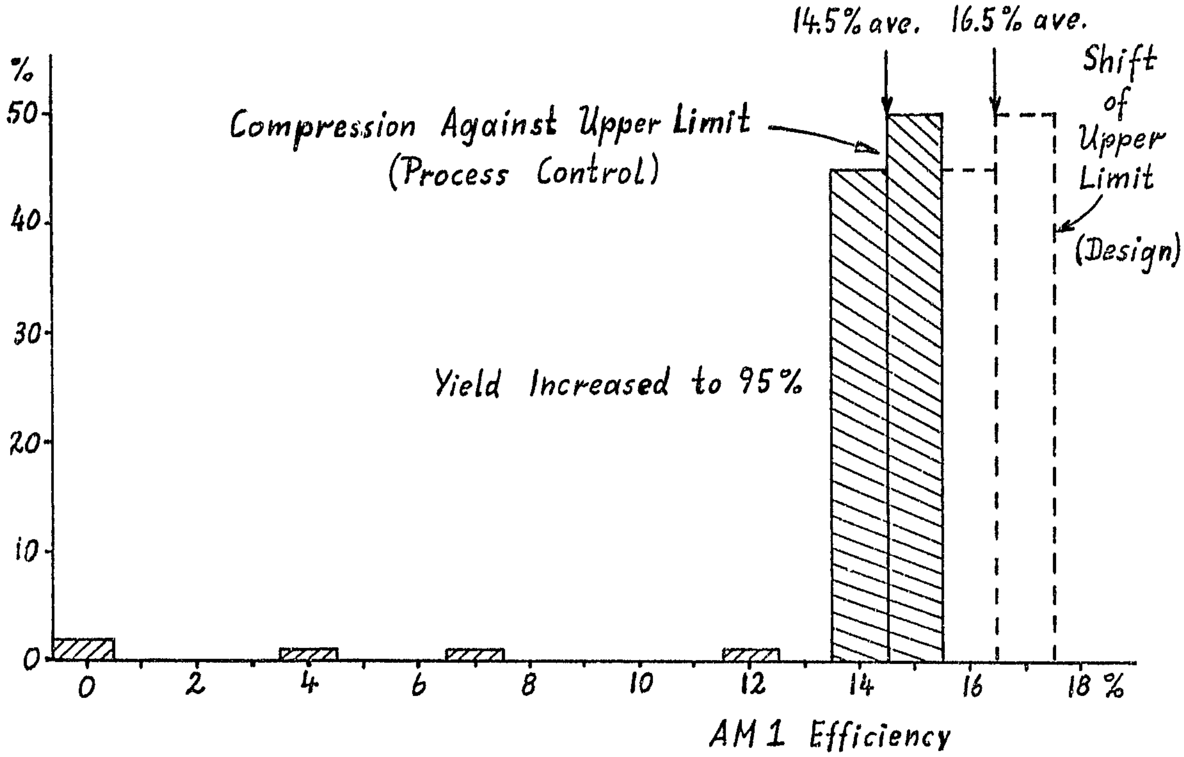
NEED: RESEARCH INTO INTERFACE OF SI AND METAL. WHAT CAUSES A STRONG SI/METAL BOND? WHAT IS THE ROLE OF O? HOW CAN THICKNESS OF SiO_x LAYER BEFORE PLATING BE CONTROLLED? CAN THICKNESS OF THIS LAYER BE MEASURED AND PLATING TIME BE ADJUSTED ACCORDING TO THICKNESS? ARE OTHER MATERIALS RESPONSIBLE FOR PROBLEMS? WHAT IS THE ROLE OF CLEANING BATHS PRIOR TO PLATING?

POTENTIAL RESULT: A HIGH-YIELD, LOW-COST METALLIZATION PROCESS.

Approximate Present Efficiency Distribution



Expected Distribution After Understanding Gained

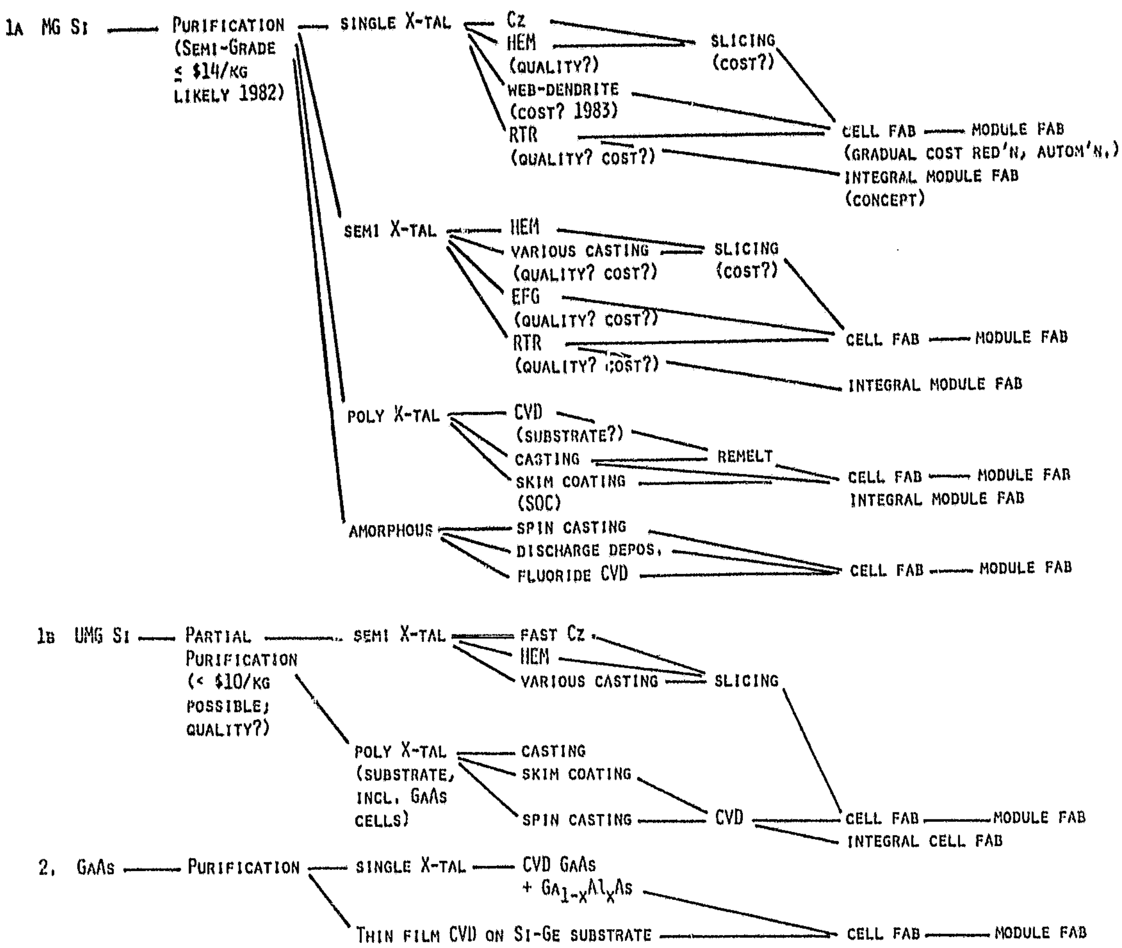


C-2

The Economic Impacts of Process Control and Cell Design

		CURRENT TERR'L CELL TECHNOLOGY CURRENT PROCESS EXPERIENCE	CURRENT TERR'L CELL TECHNOLOGY ADVANCED PROCESS-CONTROL	BEST PRESENT CELL TECHNOLOGY ADVANCED PROCESS-CONTROL
MODULE EFFICIENCY	%	11	12.3	14
MODULE VALUE (AR-BOS=0)	\$/W(P)	0.70	0.70	0.70
VALUE OF GOOD CELLS	\$/M^2	49	58	70
DTO.	\$/W(P)	0.445	0.47	0.50
VALUE OF CELL PROCESS (BEFORE YIELD)	\$/M^2	39	55	67
FOR CONSTANT SYSTEM PRICE (AR-BOS=\$60/M^2)				
MODULE VALUE	\$/W(P)	0.70	0.755	0.816
VALUE OF GOOD CELLS	\$/M^2	49	65	86
DTO.	\$/W(P)	0.445	0.53	0.615
VALUE OF CELL PROCESS (BEFORE YIELD)	\$/M^2	39	62	82

The Options to Process Cost Reduction

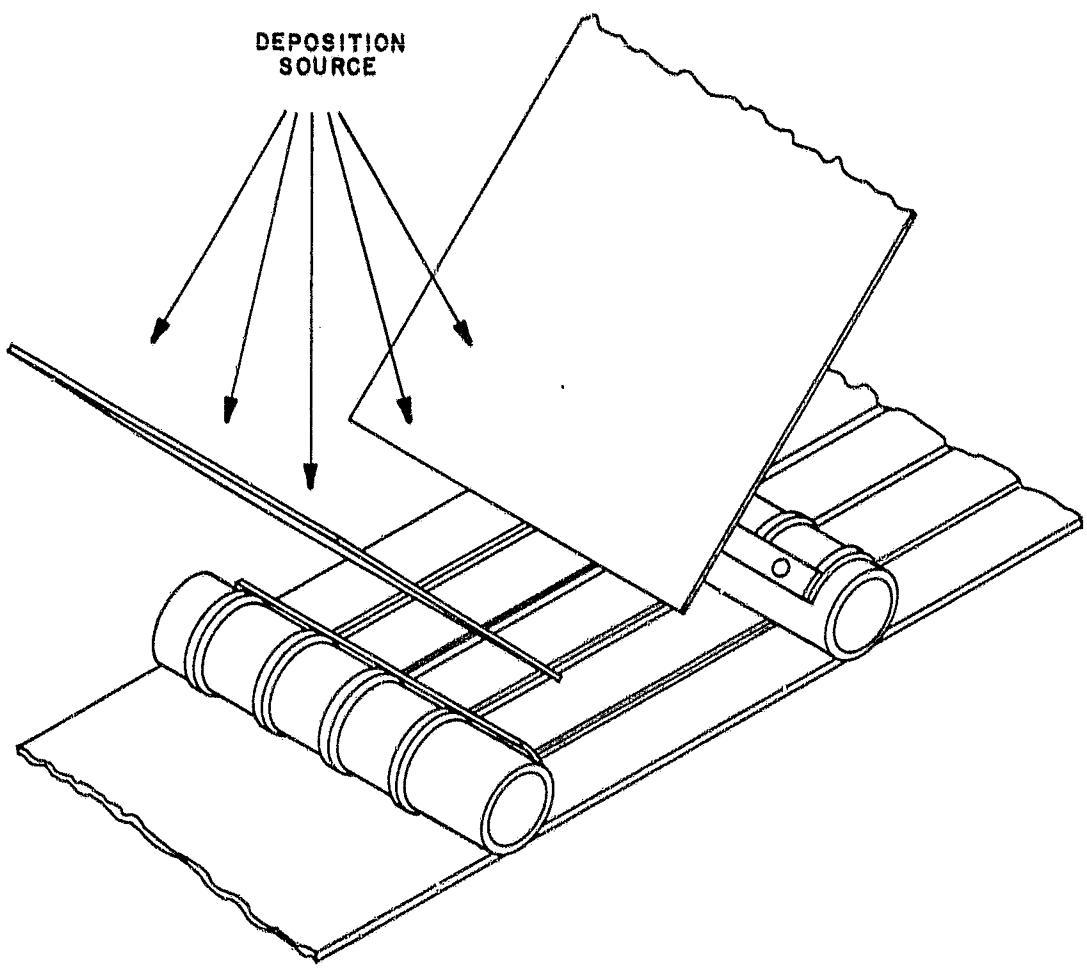


3. CdTe (COMMERCIAL?)
4. InP
5. OTHER BINARY COMPOUNDS (WILL BENEFITS JUSTIFY DEVELOPMENT COSTS?)
6. Cu In Se/CdS (HOPEFUL AS A THIN FILM DEVICE)
7. OTHER TERNARY AND HIGHER ORDER COMPOUNDS (WILL BENEFITS JUSTIFY DEVELOPMENT COSTS?)
8. MULTI BANDGAP SYSTEMS — OPTICAL BEAM SPLITTING
   — INTEGRAL CELL APPROACH (MULTIPLE LOAD CIRCUITS?)

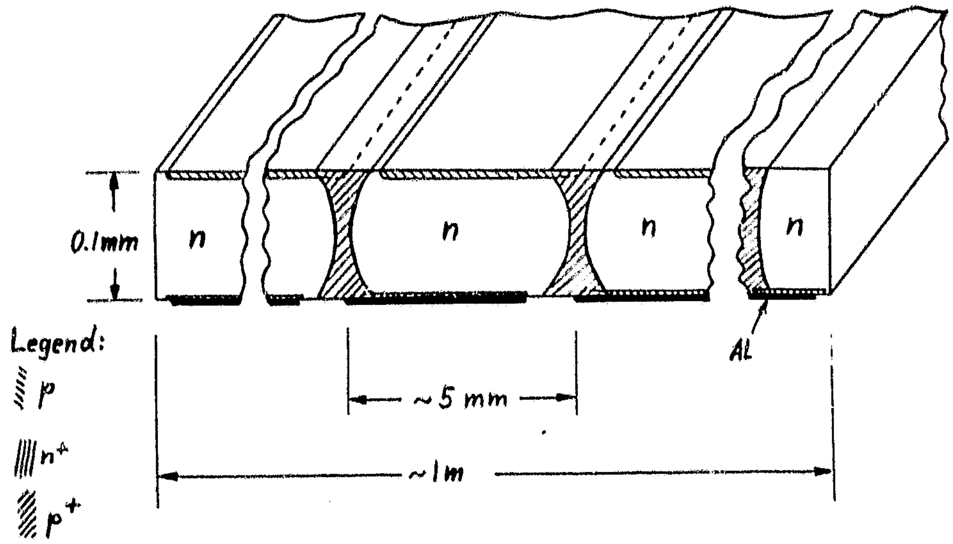
The Options

1.	TECHNOLOGY EVOLUTION:	SUCCESSFUL IN CZ, SLICING, CELL FAB, MODULE FAB. INTEGRATED PROCESSING. (LONG-RANGE PROGRESS OFTEN HARD TO PREDICT BECAUSE OF SUCCESSIVE NATURE.)
2.	TECHNOLOGY ADAPTATION: (OFTEN COMBINED WITH 1.)	SAPPHIRE TECHNOLOGY ADAPTED TO SI IN EFG AND HEM (PARTIALLY SUCCESSFUL) ION IMPLANTATION IN LIEU OF DIFFUSION. LASER SCRIBING IN LIEU OF ETCHING. SI-CASTING. RTR RIBBON PROCESS.
3.	TECHNOLOGY NEW-START: (OFTEN COMBINED WITH 2.)	SI PURIFICATION BY SiH_4 PROCESS (APPARENTLY SUCCESSFUL.) WEB-DENDRITE RIBBON PROCESS (SLOW, APPARENTLY SUCCESSFUL.) SOC. PLASMA PROCESSES (DEPOSITION, ETCHING). PULSE ANNEALING. MATERIAL COMBINATIONS (SI-GE-GAAS, $Ga_{1-x}Al_xAs$-GAAS). MULTI-BANDGAP SYSTEMS. INTEGRATED MODULE.

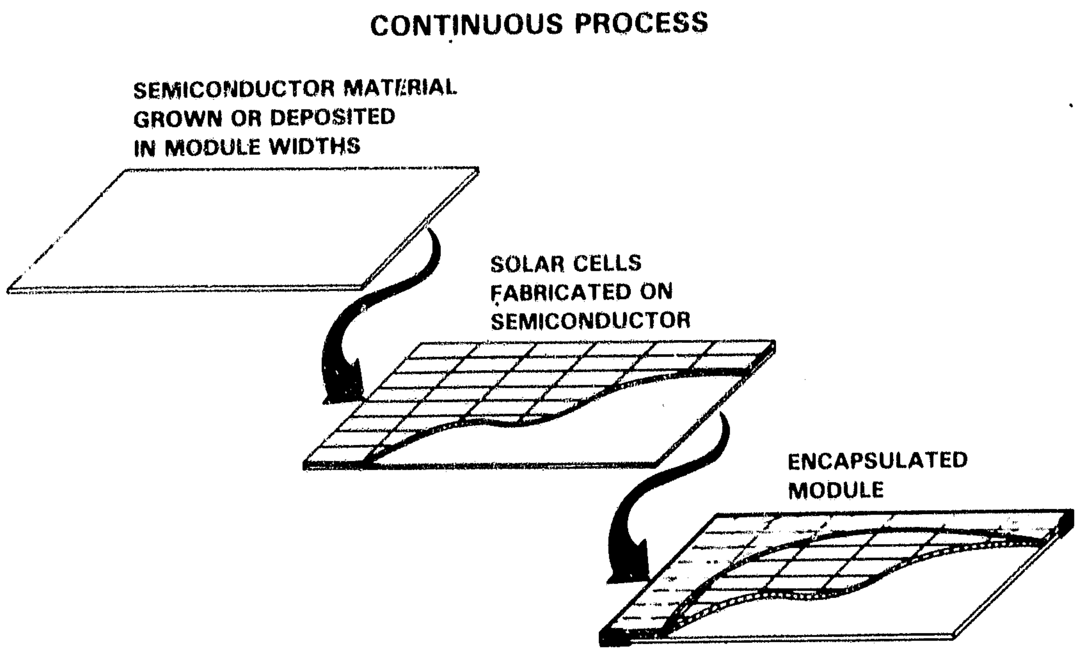
Simple Masking Method for One-Dimensional Patterns

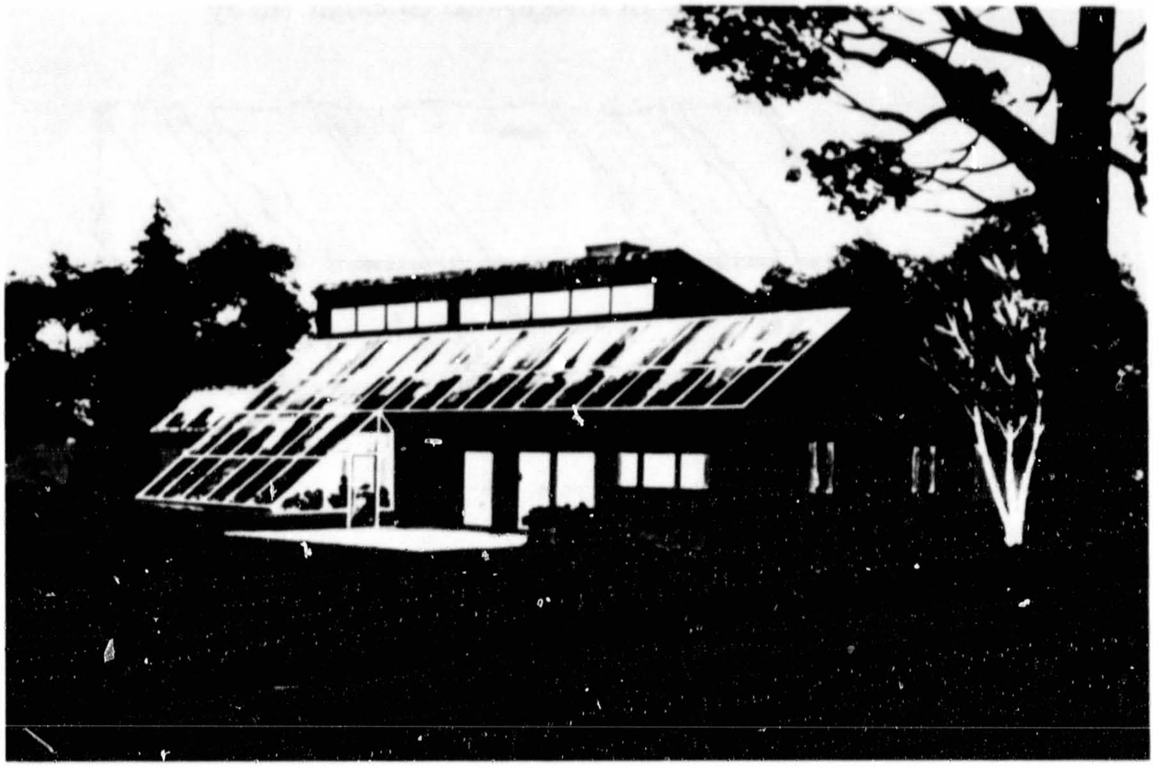


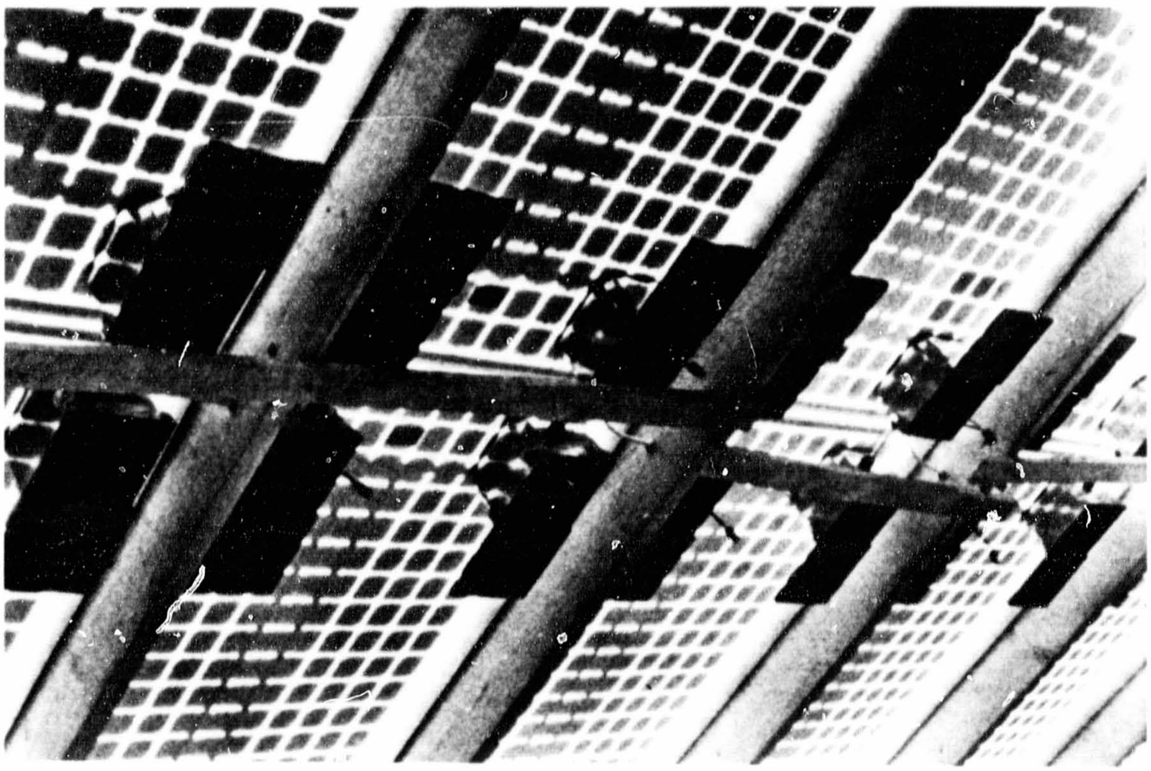
Basic Structure of Integrated Si Solar Array



Module Fabricated With Integrated Cells: Concept







Likely Technology Trends

1.) Economical systems through < High performance (single X-tal?) / Low price (thin film, poly X-tal, amorphous?) } (Bipolar vs. FET)
2.) Cell efficiencies ~ 20% single bandgap, ~ 30% multibandgap. Module prices in \$0.40 to 2.00/W(p) range, depending on performance.
3.) Si will remain a competitor.
4.) Any approach involving slicing (sawing) unlikely to succeed (sleeper?).
5.) Can semi-crystal and low-quality substrate approaches yield enough price/performance margin to survive?
6.) Evolution to integrated, continuous processing (batch or quasi-batch should disappear).
7.) Integrated modules, requiring wide sheet.
8.) Not all possibilities can be pursued. Thus, there will always be other options. (Criterion: Lowest risk/benefit ratio, but how to assess?)

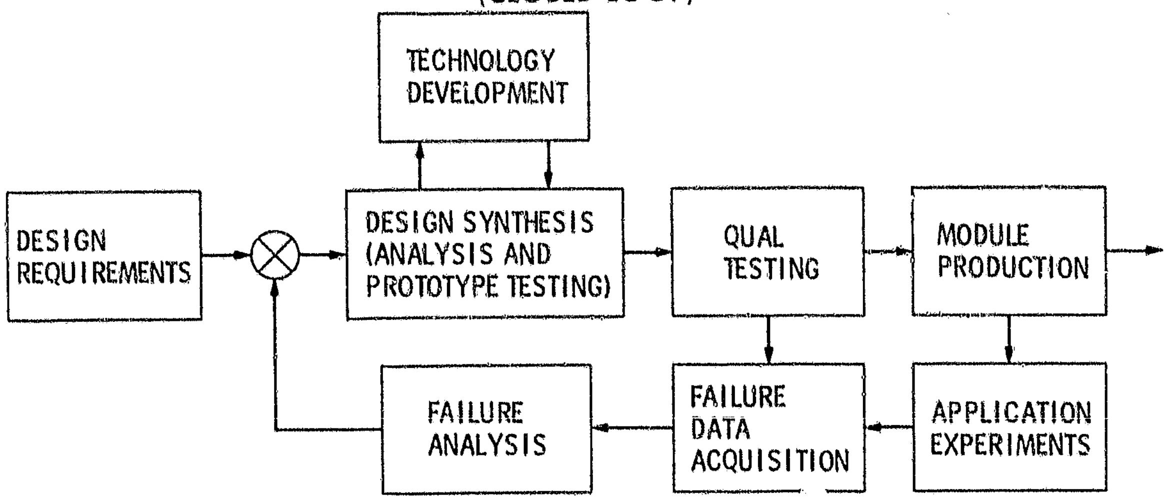
EVOLVING MODULE AND ARRAY TECHNOLOGY

JET PROPULSION LABORATORY

R.G. Ross Jr.

Module and Array Development Process

(CLOSED LOOP)



APPROACH

- SPECIFY REQUIREMENTS
- SYNTHESIZE DESIGNS
- SCREEN DESIGNS USING QUAL TESTS
- ACQUIRE AND FEED BACK PERFORMANCE DATA
- DEVELOP IMPROVED TECHNOLOGIES
- USE FEEDBACK AND TECHNOLOGY TO IMPROVE DESIGNS

Module and Array Technology

CELL OBJECTIVE ▪ ELECTRICAL PERFORMANCE AT LOW COST ($/WATT)

MODULE/ARRAY OBJECTIVE ▪ ENVIRONMENTAL ENDURANCE, RELIABILITY, AND SAFETY AT LOW COST ($/$m^2$)

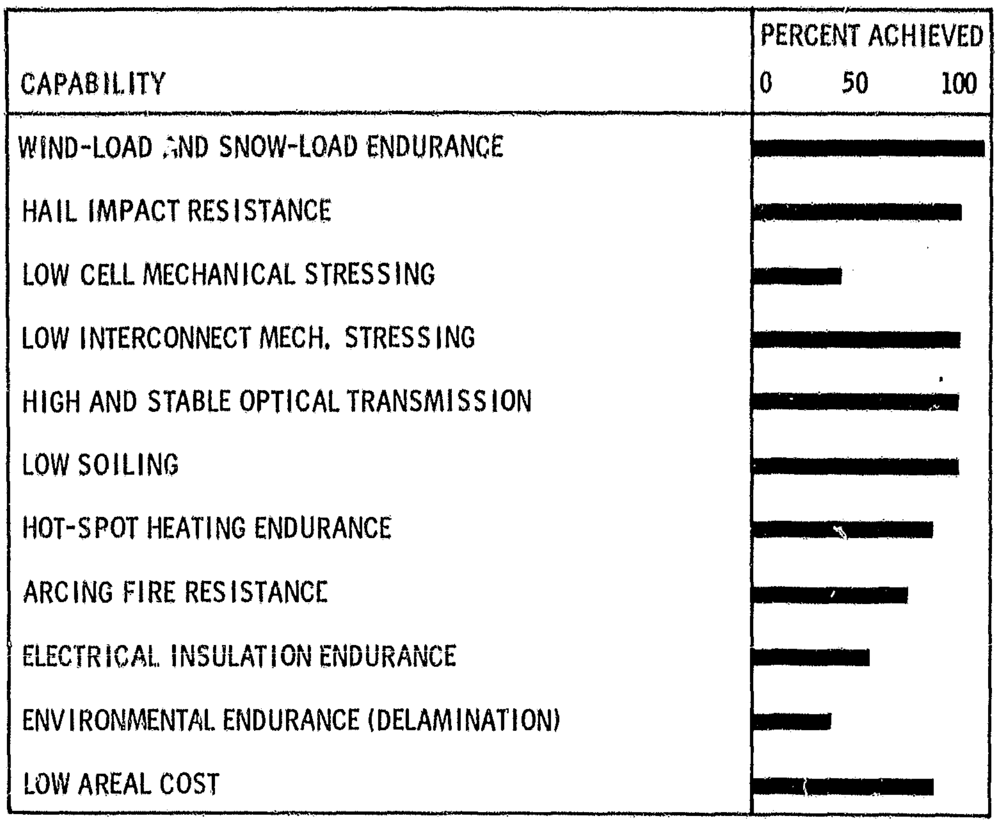
MODULE AND ARRAY ELEMENTS:

- ENCAPSULANT SYSTEM
- ELECTRICAL CIRCUIT
- SUPPORT STRUCTURE
  - GROUND-MOUNTED
  - RESIDENTIAL ROOF-MOUNTED

Encapsulant System Objectives

- PROTECT CELL FROM ENVIRONMENTAL STRESSES
  - WIND AND SNOW
  - HAIL
  - DIFFERENTIAL EXPANSION
  - HUMIDITY
- MAXIMIZE SUNLIGHT TO CELL
  - OPTICAL TRANSMISSION
  - LOW SOILING
- PROTECT USER FROM SAFETY HAZARDS
  - ELECTRICAL
  - FIRE
- MAINTAIN 20-YEAR LIFETIME
- MAINTAIN LOW AREAL COST

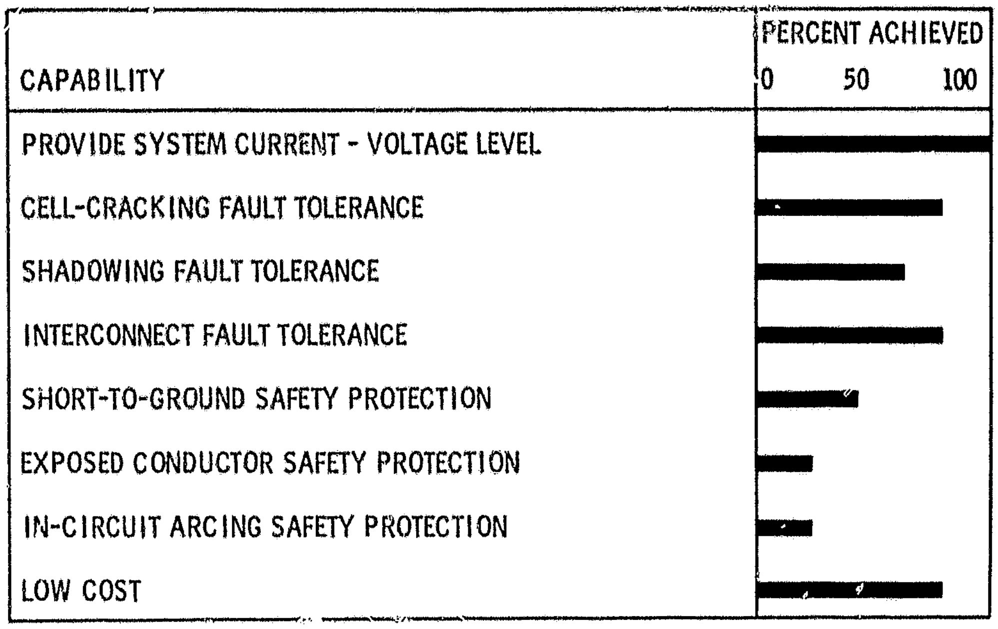
Encapsulation Technology Status



Electrical Circuit Objectives

- PROVIDE VOLTAGE CURRENT LEVELS REQUIRED BY SYSTEM
- PROVIDE FAULT TOLERANCE AGAINST CELL AND CIRCUIT FAILURES
  - CELL CRACKING
  - PARTIAL SHADOWING
  - INTERCONNECT OPEN CIRCUITS
- PROVIDE SAFETY PROTECTION AGAINST CIRCUIT/ENCAPSULANT FAILURES
  - CIRCUIT TO FRAME GROUND FAULTS
  - EXPOSED LIVE CIRCUIT ELEMENTS
  - IN-CIRCUIT OR GROUND FAULT ARCING
- MAINTAIN LOW COST

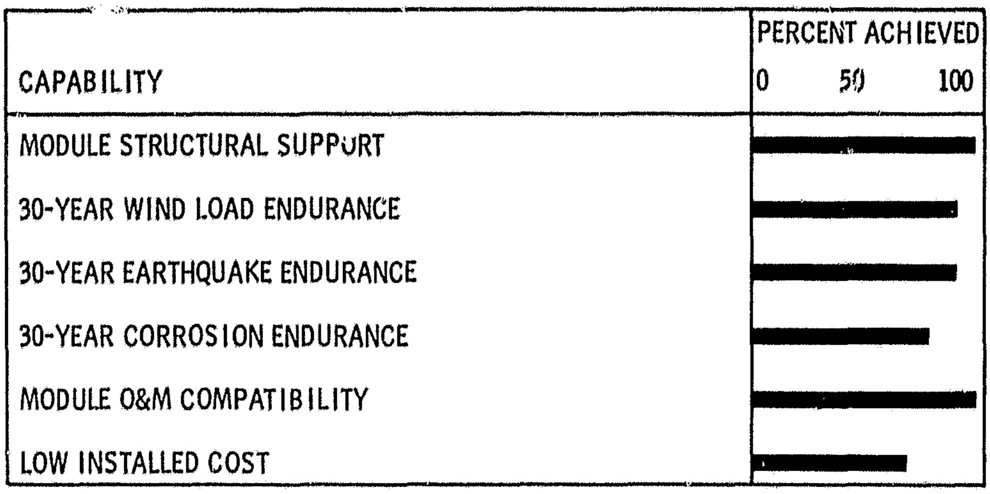
Electrical Circuit Status



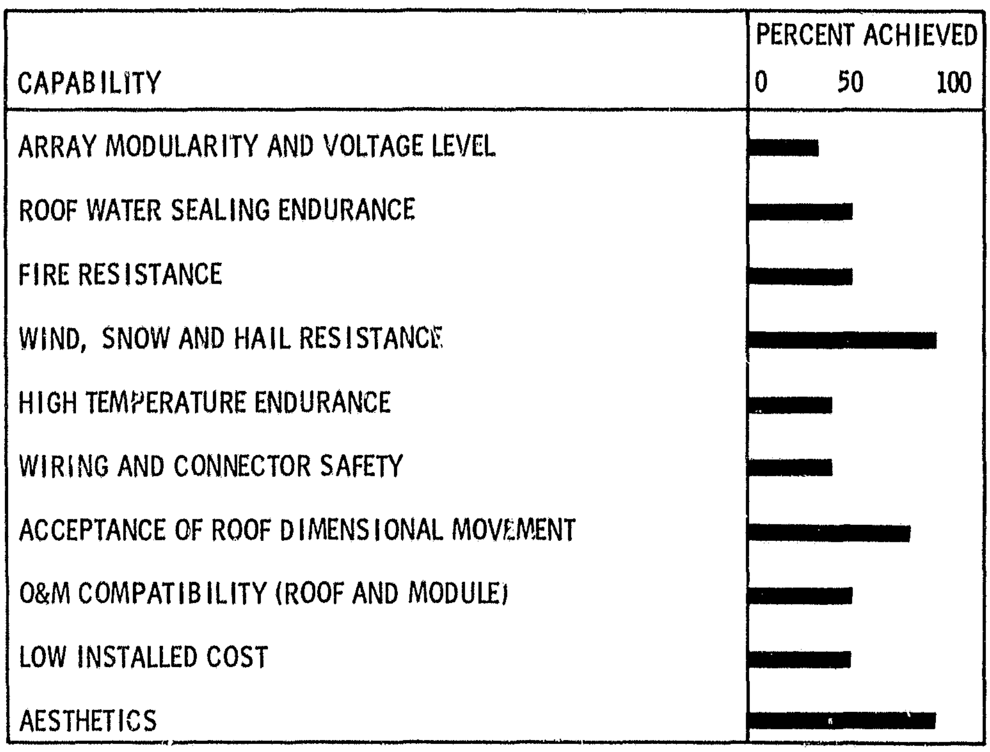
Support Structure Objectives

- SUPPORT MODULES
  - ORIENTATION
  - LOADS
- MAINTAIN 30-YEAR LIFETIME
  - WIND AND SNOW
  - EARTHQUAKES
  - CORROSION
- PROVIDE FOR OPERATION AND MAINTENANCE
  - MODULE ATTACHMENT AND REMOVAL
  - CLEANING
- MAINTAIN LOW INSTALLED COST

Ground-Mounted Structures Status



Residential Roof-Mounted Array Status



Conclusions

- SUBSTANTIAL PROGRESS HAS BEEN ACHIEVED
    - IMPROVED ENCAPSULANTS (GLASS, EVA, ACRYLICS)
        - LOW COST LAMINATION PROCESSING
        - GOOD OPTICAL STABILITY (LOW SOILING)
        - HAIL RESISTANCE
    - IMPROVED FAULT TOLERANCE
        - CELL AND INTERCONNECT FAILURE
        - HOT-SPOT ENDURANCE
    - LOW-COST GROUND-MOUNTED STRUCTURES
- A NUMBER OF TECHNOLOGY GAPS REMAIN
    - SOLAR CELL BREAKAGE
    - ENCAPSULANT ENDURANCE (LONG LIFE)
    - MODULE AND ARRAY ELECTRICAL SAFETY
    - ROOF-MOUNTED ARRAY TECHNOLOGIES

INDUSTRY PERSPECTIVE

PHOTOWATT INTERNATIONAL, INC.

R. McGinnis

ASSUMPTION: SINGLE, POLYCRYSTALLINE
OR RIBBON SILICON WILL BE THE
DOMINANT MATERIAL IN THE NEXT 5-15 YEARS

EXACT YEAR-BY-YEAR

MARKET PROJECTIONS

Overall Business Strategy

TECHNOLOGY DEVELOPMENTS AND MANUFACTURING INVESTMENTS WILL DRIVE THE COST OF SOLAR POWER SYSTEMS DOWN.

AS THIS OCCURS, THE ECONOMIC MARKETS WILL INCREASE BECAUSE THE COSTS OF TRADITIONAL METHODS OF REMOTE POWER GENERATION WILL BE UNDERCUT.

WHEN THE COSTS OF PV SYSTEMS BEGIN TO COMPETE WITH NEAR-GRID AND ON-GRID POWER GENERATION, THE MARKETS WILL GROW EXPONENTIALLY.

TRADITIONAL POWER SYSTEM COST INCREASES IN EXCESS OF INFLATION WILL SERVE TO ACCELERATE THIS GROWTH.

The Dilemma

SIGNIFICANT MANUFACTURING INVESTMENTS IN LIMITED LIFETIME TECHNOLOGIES CAN BE A VERY COSTLY BUSINESS STRATEGY.

MAJOR INVESTMENTS IN TECHNOLOGY WITHOUT SIMULTANEOUS MARKET DEVELOPMENT COULD MAKE LATE ENTRY VERY DIFFICULT AND EXPENSIVE, EVEN WITH A LOWER COST PRODUCT.

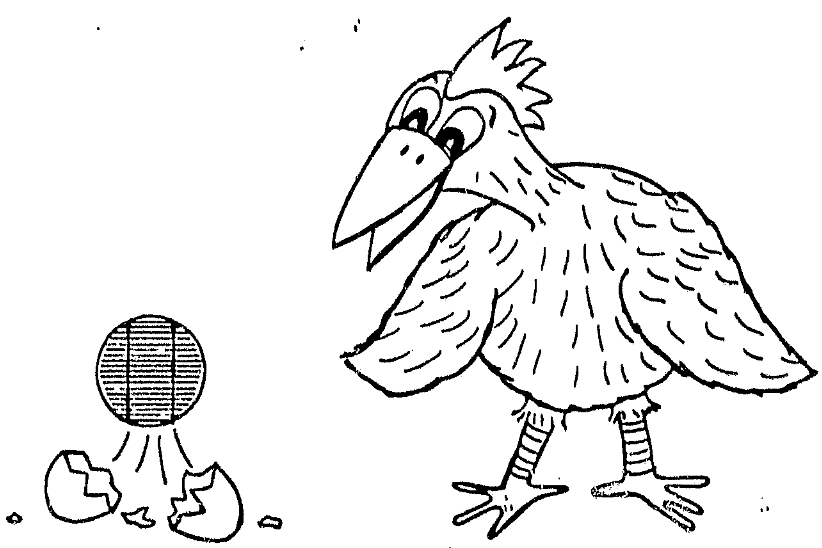
THE GOVERNMENT PROGRAM, WITH ITS PUBLISHED TIME-PHASED COST GOALS, HAS CAUSED UNJUSTIFIED EARLY PRICE PRESSURE WHICH SEVERLY ERODED MARGINS.

The Strategies

	EARLY MARKET SHARE	LONG-TERM TECHNOLOGY DEVELOPMENT
DESCRIPTION:	GAIN MARKET SHARE BY AGGRESSIVE PRICING AND INVESTMENT IN MANUFACTURING CAPACITY AND AUTOMATION.	CURRENT MARKETS ARE SECONDARY OR IGNORED. MAJOR INVESTMENT IN TECHNOLOGY DEVELOPMENT.
RISKS:	MARGINS LOW OR NEGATIVE, DUE TO AGGRESSIVE PRICING, NEEDED TO GAIN MARKET SHARE. SIGNIFICANT INVESTMENTS IN PLANT AND EQUIPMENT, WHICH COULD BECOME OBSELETE LONG BEFORE END OF USEFUL LIFE. MARKET MAY BE SMALLER OR DEVELOP SLOWER THAN FORECASTED.	TECHNOLOGY DEVELOPED MAY NOT MEET NEEDED COST GOALS. RAPID PRODUCTION BUILD UP OF NEW TECHNOLOGY WILL BE COSTLY. TECHNOLOGY MAY TAKE MUCH LONGER TO DEVELOP THAN EXPECTED. MARKETING AND DISTRIBUTION CHANNELS MAY BE IRREVOCABLY LOST.
REWARDS:	EARLY MARKET SHARE GAINS ARE FAR LESS COSTLY THAN AT THE TIME WHEN COMPETITORS ARE FURTHER DOWN THE LEARNING CURVE.	CAN DEVELOP THE "MODEL T" OF THE SOLAR INDUSTRY AND SWEEP ASIDE ALL COMPETITORS WITH LOW COST PRODUCTS.

MOST COMPANIES ARE ATTEMPTING TO STRIKE A BALANCE BETWEEN THE TWO EXTREMES. THE ROLE OF GOVERNMENT IN BOTH PRODUCT PROCUREMENT AND TECHNOLOGY DEVELOPMENT FUNDING CAN HAVE A SIGNIFICANT EFFECT ON THE AMOUNT AND TYPE OF RESOURCES THAT THE COMPANY MUST PROVIDE.

Which Will Come First?



IF THE COST OF SILICON DOES NOT
DROP SIGNIFICANTLY, THERE WILL
BE NO SOLAR MARKET, AND IF THERE
IS NO SOLAR MARKET, THERE IS
NO REASON FOR THE MATERIAL SUPPLIERS
TO INVEST LARGE SUMS OF MONEY
IN LOW COST SILICON MANUFACTURING.

GOVERNMENT FUNDING OF TECHNOLOGY
DEVELOPMENT PROVIDES RISK REDUCTION

ALTERNATIVE TO GOVERNMENT FUNDING
MUST COME FROM <u>WELL-HEELED SOLAR</u>
<u>COMPANIES</u> WHO WILL FUND THIS
DEVELOPMENT INTERNALLY FOR
<u>THEIR EXCLUSIVE USE</u>

Near-Term Perspective (One to Five Years)

- GREAT DEAL OF SHIFTING AND CONFUSION REGARDING THE GOVERNMENT POSITION VIS-A-VIS THE SOLAR BUSINESS
- MODERATE GROWTH OF THE COMMERCIAL INDUSTRIAL MARKET
- GROWING AWARENESS OF THE DOMESTIC CONSUMER OF THE POTENTIAL OF PHOTOVOLTAICS

Cost Trends

- COSTS WILL TEND TO FLATTEN OUT IN THE SHORT TERM DEPENDING ON THE PROCESS COST, DEGREE OF VERTICAL INTEGRATION AND EXTENT OF AUTOMATION
- COST OF SILICON SHEET STILL DOMINANT FACTOR IN OVERALL MODULE COSTS

Business Trends

- LARGE SOLAR COMPANIES WILL PURSUE INTERNALLY FUNDED PROGRAMS FOR TECHNOLOGY DEVELOPMENT OR DROP OUT OF THE BUSINESS
- SMALL SOLAR COMPANIES WILL CONTINUE TO LOOK FOR POTENTIAL LARGE BUYERS IN ORDER TO STAY IN THE GAME
- MATERIALS SUPPLIERS HAVE THE MOST DIFFICULT DECISIONS TO MAKE

Prospects

- PHOTOVOLTAICS WILL BECOME A PART OF THE WORLD'S ENERGY SUPPLY.
- THE OVERALL INVESTMENTS THAT WILL BE MADE WILL BE LARGE.
- THE ULTIMATE MARGINS WILL BE COMPARABLE TO THOSE IN OTHER FORMS OF ENERGY SUPPLY.
- THE EXISTING ENERGY COMPANIES WILL PLAY A MAJOR ROLE IN THE FUTURE OF PV BUSINESS.
- THE PV BUSINESS WILL DEVELOP MORE SLOWLY THAN ANTICIPATED BUT WILL BE A MUCH LARGER MARKET THAN WE NOW FORECAST.

WAFERING WORKSHOP SUMMARY

PHOENIX, ARIZONA, JUNE 8-10, 1981

JET PROPULSION LABORATORY

- INTRODUCTION
- HIGHLIGHTS OF TECHNICAL PRESENTATIONS
- CONCLUSIONS
- 27 PAPERS
- 86 ATTENDEES
- INDUSTRY, GOVERNMENT, UNIVERSITY AND INTERNATIONAL REPRESENTATION
- 30% FROM CORPORATE MANAGEMENT

Objectives

- ASSESS THE STATE-OF-THE-ART IN SILICON WAFERING
- INVITE AND EXPLORE INNOVATIVE IDEAS IN WAFERING
- STIMULATE PRODUCTIVE EXCHANGE OF INFORMATION WITHIN THE WAFERING COMMUNITY

Sessions

1. OPENING
2. ID TECHNOLOGY
3. MULTIPLE BLADE TECHNOLOGY
4. MATERIALS
5. CHARACTERIZATION
6. NEW TECHNOLOGY
7. ECONOMICS

Critical Elements of Wafering Technology

- BLADE/WIRE DEVELOPMENT
- LOW KERF, THIN WAFERS
- HIGH THROUGHPUT SLICING
- EXPENDABLE MATERIALS USAGE

Technology Drivers

- MATERIAL CONSERVATION
- HIGH THROUGHPUT

PRESENTATIONS

"KINEMATICAL AND MECHANICAL ASPECTS OF WAFER SLICING"
- P. G. WERNER

- A NEW MODEL OF WORK-TOOL INTERACTIONS AND PERTINENT MICRO-MECHANICS OF MATERIAL REMOVAL FOR A SLURRY SAWING PROCESS IS PRESENTED
- RESULTANT FUNCTIONAL EXPRESSIONS RELATING PROCESS CRITERIA (e.g. CUTTING RATE, TOOL WEAR) TO PROCESS PARAMETERS (e.g. STROKE LENGTH, FREQUENCY AND FORCE) ARE DERIVED
- MATERIAL REMOVAL RATE IS DIRECTLY PROPORTIONAL TO BLADE LOAD AND SLICING SPEED
- OPTIMUM SLICING CONDITIONS ARE ACHIEVED WHEN BLADE AND WORKPIECE CUTTING CONTOURS HAVE STABILIZED

"ALLOWABLE SILICON WAFER THICKNESS versus DIAMETER FOR ROTATION INGOT ID WAFERING" - C.P. CHEN et al

- FRACTURE MECHANICS ANALYSIS WAS UTILIZED TO ANALYZE THE LOADING CONDITIONS UPON A WAFER DURING WAFERING
- THE ALLOWABLE WAFER THICKNESS versus INGOT DIAMETER WAS FOUND TO BE DEPENDENT ON THE DEPTH OF SURFACE DAMAGE, SAW VIBRATION AND CUTTING RATE
- APPLICATION OF A TENSIONAL FORCE PERPENDICULAR TO THE WAFER SURFACE DURING WAFERING CAN ENHANCE CLEAVAGE OF <111> SILICON INGOTS AND POINTS TO A POTENTIAL FOR REDUCTION OF MINIMAL OBTAINABLE WAFER THICKNESS

"EXIT CHIPPING IN ID SAWING OF SILICON CRYSTALS"
— L. D. DYER

- STUDY RELATES THE EXISTENCE AND AMOUNT OF EXIT-CHIP OR SAW FRACTURE FORMATION TO ID WAFERING PARAMETERS
- FRACTURE FORMATION IS ORIENTATION-DEPENDENT
- EXIT CHIP SIZE INDICATES 'HARSHNESS' OF SAWING CONDITION

"EFFECT OF LUBRICANT ENVIRONMENT ON SAW-INDUCED DAMAGE IN SILICON WAFERS" - T. S. KUAN et al

- CHEMOMECHANICAL EFFECT OF DIFFERENT LUBRICANT SOLUTIONS UPON SAW-INDUCED DAMAGE
- EFFECT OF APPLIED ELECTRIC POTENTIAL ON SILICON CRYSTAL DURING WAFERING
- LUBRICANTS ARE GOOD CATALYSTS FOR BREAKING SILICON BONDS AND CAN DAMPEN OUT-OF-PLANE BLADE VIBRATIONS
- EXPERIMENTAL DATA SHOWS A 30-50% REDUCTION IN SAW-INDUCED DAMAGE WITH A PROPER LUBRICANT ENVIRONMENT

"INFLUENCE OF FLUIDS ON THE ABRASION OF SILICON BY DIAMOND" - S. DANYLUK

- THE WEAR RATE OF SILICON IS IN THE RATIO OF 1:2:3 FOR WATER, ETHANOL AND ACETONE, RESPECTIVELY, FOR A CONICAL DIAMOND ABRADING SILICON AT ROOM TEMPERATURE
- ABRASION MODE CHANGES FROM BRITTLE TO DUCTILE WHEN FLUID IS CHANGED
- SUBSURFACE CRACKS (SAW-INDUCED DAMAGE) PRESENT ARE AFFECTED IN MAGNITUDE BY THE FLUID ENVIRONMENT
- SURFACE HARDNESS OF SILICON IS INFLUENCED BY THE DIELECTRIC CONSTANT OF FLUID

"CORROSION INHIBITORS FOR WATER-BASED SLURRY MULTIPLE BLADE SAWING" - C. P. CHEN et al

- FAILURES OF HIGH CARBON STEEL BLADES USING WATER-BASED SLURRIES ARE DUE TO STRESS CORROSION INDUCED BY AN OXYGEN CONCENTRATION CELL EFFECT AND RESIDUAL AND CYCLIC BLADE TENSION LOADS
- FOUR CORROSION INHIBITOR/WATER SOLUTIONS HAVE BEEN IDENTIFIED WITH SIGNIFICANT POTENTIAL FOR WATER-BASED SLURRY MULTIPLE BLADE WAFERING APPLICATIONS

"FUNDAMENTAL STUDIES OF THE SOLID-PARTICLE EROSION OF SILICON" - J. L. ROUTBORT et al

- EXISTING MODELS OF SOLID-PARTICLE EROSION OF BRITTLE MATERIALS ARE MODIFIED FOR THE CASE OF SILICON SINGLE CRYSTALS
- SYSTEMATIC EXPERIMENTS ARE NEEDED TO PROVIDE DATA TO INCORPORATE THE EFFECTS INTO A PREDICTIVE MODEL FOR EXISTING WAFERING TECHNIQUES
- SOME PROJECTILE PROPERTIES (PARTICLE SHAPE AND HARDNESS) ARE FACTORS YET TO BE INVESTIGATED

"PRE AND POST ANNEALING OF MECHANICAL DAMAGE IN SILICON WAFERS" - G. H. SCHWUTTKE

- BASIC PROPERTIES OF MECHANICAL DAMAGE IN SILICON WERE STUDIED USING TEM
- ABRASION DAMAGE CONSISTS PRIMARILY OF SHEAR LOOPS THAT FREQUENTLY RESULT IN SUB-MICRON CRACKS DUE TO DISLOCATION PILE-UPS
- HIGH TEMPERATURE ANNEALING OF THESE CRACKS RESULT IN DISLOCATIONS AND STACKING FAULTS
- THEIR PRESENCE REDUCES THE MINORITY CARRIER LIFETIME OF THE SILICON MATERIAL
- CHEMICAL ETCHING REQUIRES REMOVAL OF UP TO FOUR TIMES THE ORIGINAL DAMAGE DEPTH BECAUSE OF CRACK PROPAGATION DURING ETCHING

"WAFERING INSIGHT PROVIDED BY THE ODE METHOD" - S. I. SOCLOF et al

- ORIENTATION-DEPENDENT SLICING USES PREFERENTIAL ETCHING OF NARROW SLOTS ON A SILICON SLAB TO FORM SLICES
- ADVANTAGES INCLUDE HIGH MATERIAL YIELD (m^2/kg), PLANE PARALLEL SURFACES AND VERY THIN SLICES ($50\ \mu m$) WITH NO SURFACE DAMAGE

"SYSTEM FOR SLICING SILICON WAFERS" - E. R. COLLINS

- NEWLY-PATENTED PROCESS FOR EFFICIENT SLICING OF A LARGE NUMBER OF INGOTS IN A HIGH SPEED MODE

- COMBINES ADVANTAGES OF A MULTIPLE BLADE WAFERING PROCESS, FIXED ABRASIVES AND HIGH BLADE VELOCITIES

HIGHLIGHTS SUMMARY

SILICON INGOT → WAFERING PROCESS → SILICON WAFER

<u>INGOT</u>

- ORIENTATION
- BASIC MATERIAL PROPERTIES
- CRYSTALLINITY
- SHAPE AND SIZE

<u>WAFERING PROCESS</u>

CUTTING FLUID

- LUBRICANT
- COOLANT
- SURFACE MODIFIER
- CORROSION INHIBITOR
- ELECTROLYTE
- MECHANICAL DAMPING
- PARTICLE CARRIER

CUTTING PARTICLE

- SHAPE
- SIZE
- MATERIAL PROPERTIES
- 'ACTION'

WAFERING PROCESS

CUTTING BLADE
- MATERIAL PROPERTIES
- ABRASIVE BONDING (FIXED ABRASIVE WAFERING)
- BLADE CONTOUR (LOOSE ABRASIVE WAFERING)
- 'ACTION'

SILICON WAFER
- SAW-INDUCED DAMAGE
- FRACTURE PROPERTIES
- ORIENTATION
- SIZE

Conclusions

1. WAFERING IS A MAJOR FACTOR IN DETERMINING THE SUCCESS OF INGOT TECHNOLOGY FOR LOW-COST SOLAR ARRAYS

2. CONSIDERABLE OPPORTUNITIES EXIST TO ADVANCE WAFERING TECHNOLOGY SIGNIFICANTLY THROUGH BASIC INVESTIGATIONS INTO THE FUNDAMENTAL MECHANISMS OF WAFERING

Technology Sessions

TECHNOLOGY DEVELOPMENT AREA

Silicon Material Task

Ralph Lutwack, Chairman

Reports on progress in developing Si processes and in supporting activities were presented by five contractors and by JPL.

Union Carbide Corp. reviewed the status of its effort to build an EPSDU (experimental process system development unit). All civil and structural work is complete, the bulk of equipment has been delivered to the site at East Chicago, Indiana, and most major pieces have been placed in position. In the R&D area, the silicon (Si) powder melter and shotter was assembled and put into operation. Using chunk Si as feed material, the unit produced free-flowing shot for periods up to 45 minutes. The fluidized-bed process development unit (PDU) was assembled, and an initial series of tests with mixtures of 10% to 21% silane (SiH_4) in hydrogen was successfully completed.

Massachusetts Institute of Technology summarized the results of its two-year contract to develop a process for making trichlorosilane ($SiHCl_3$) by the hydrochlorination of metallurgical-grade Si and silicon tetrachloride ($SiCl_4$). The contract ended, and the follow-on effort at Solarelectronics, Inc., was started.

Hemlock Semiconductor Corp. completed construction of the PDU for investigating the rearrangement of $SiHCl_3$ to dichlorosilane (SiH_2Cl_2), integrated the unit with an intermediate-scale Siemens-type reactor, and conducted 17 tests by the end of June.

Westinghouse R&D Center completed all experimental phases of the impurity study, and presented a summary of the entire program, including the effects of specific impurities on the performance of both n-base and p-base solar cells and the effects of gettering.

Design calculations for cell efficiency, open-circuit voltage, short-circuit current, and fill factor as functions of cell thickness were presented by C. T. Sah Associates.

Progress in two in-house JPL programs (research on the operation of fluidized bed reactors for depositing Si from SiH_4, and the conversion of SiH_4 to molten Si in a one-step process) was reported.

POLYCRYSTALLINE SILICON

UNION CARBIDE CORP.

TECHNOLOGY

POLYCRYSTALLINE SILICON

REPORT DATE

7/15/81

APPROACH

HIGH-PURITY SILANE PRODUCTION FROM METALLURGICAL-GRADE SILICON; AND SILANE PYROLYSIS AND CONSOLIDATION TO FORM SEMICONDUCTOR-GRADE POLYCRYSTALLINE SILICON

CONTRACTOR

UNION CARBIDE CORPORATION

GOALS

- DEMONSTRATE PROCESS FEASIBILITY AND ENGINEERING PRACTICALITY.
- ESTABLISH TECHNOLOGY READINESS USING "EPSDU" SIZED TO 100 MT/YR.
- SILICON PRICE OF LESS THAN $14/KG FOR HIGH VOLUME PROCESS.
- DEFINE PROCESS ECONOMICS.

STATUS

ENGINEERING & INSTALLATION WORK ON THE EPSDU

- THE CIVIL-STRUCTURAL SUBCONTRACT COMPLETED.
- ALL MAJOR EQUIPMENT DELIVERED TO EPSDU SITE.
- THE MECHANICAL INSTALLATION DRAWING PACKAGE WAS COMPLETED, AND WAS SENT TO POTENTIAL BIDDERS.
- ALL BIDS WERE RECEIVED AND ARE UNDER EVALUATION.
- THE ELECTRICAL INSTALLATION DRAWING PACKAGE WAS COMPLETED AND WAS SENT TO POTENTIAL BIDDERS.
- THE MECHANICAL INSTALLATION SUBCONTRACT IS READY TO BE AWARDED IF SUFFICIENT FUNDS BECOME AVAILABLE.

SILANE PYROLYSIS R & D

- CHUNK SILICON WAS MELTED IN THE SI POWDER MELTER/SHOTTER AND ACCEPTABLE SHOT PRODUCED.
- FREE-SPACE REACTOR SI POWDER WAS MELTED IN THE SI POWDER MELTER/SHOTTER.
- 10 TO 21% SILANE IN HYDROGEN WAS FED TO THE FLUID-BED PDU FOR ~5 HOURS. DENSE POLYSILICON WAS GROWN ON THE SEED PARTICLES IN THE BED.

ASSUMPTIONS:

PLANT SIZE:	1000 MT/YR SEMICONDUCTOR-GRADE LIQUID SILICON PRODUCT*
TOTAL PLANT COST:	$9.66 MM
START-UP COST:	$1.74 MM
WORKING CAPITAL:	$0.72 MM
ANNUAL OPERATING COST:	$5.88 MM
FEDERAL INCOME TAX:	46%
CONSTRUCTION TIME:	2.5 - 3 YRS
DEPRECIATION:	10 YEARS SUM OF YEARS DIGITS
PROJECT LIFE:	15 YEARS

PROJECTION

ROI RATE, %	PRODUCT PRICE, $/KG
10	8.77
15	9.77
20	10.90

*INCREMENTAL PRODUCT PRICE INCREASE GOING FROM LIQUID SILICON TO POLYCRYSTALLINE SILICON SHOT HAS NOT BEEN DETERMINED. ONE TO TWO DOLLAR/KG INCREASE IS ANTICIPATED.

Problems and Concerns

EPSDU ENGINEERING, INSTALLATION AND OPERATION

- A PORTION OF THE WASTE TREATMENT SYSTEM DESIGN IS RELATIVELY NOVEL, AND SOME FIELD ADJUSTMENT MAY BE NEEDED FOR PROPER OPERATION.

SILANE PYROLYSIS R & D

- EROSION OF THE QUARTZ NOZZLE IN THE SI POWDER MELTING/SHOTTING SYSTEM MAY BE EXCESSIVE TO BE ECONOMICAL. A MULTIPLE NOZZLE DESIGN MAY HAVE TO BE DEVELOPED

Silane–to–Silicon EPSDU Chemistry

A. HYDROCHLORINATION

$$Si + 3\,SiCl_4 + 2\,H_2 \xrightarrow{Cu} 4\,HSiCl_3$$

B. REDISTRIBUTION

$$2\,HSiCl_3 \xrightarrow{A\text{-}21} H_2SiCl_2 + SiCl_4$$

$$3\,H_2SiCl_2 \xrightarrow{A\text{-}21} 2\,HSiCl_3 + SiH_4$$

C. SILANE ..ROLYSIS

$$SiH_4 \longrightarrow 2\,H_2 + Si$$

EPSDU Engineering Summary

A. M. G. SILICON-TO-SILANE

- PROCESS DESIGN COMPLETE
- FACILITY DESIGN COMPLETE
- MAJOR EQUIPMENT FABRICATED AND RECEIVED AT EPSDU SITE
- INSTALLATION DESIGN COMPLETE
- INSTALLATION BID PACKAGES SENT TO BIDDERS
- BIDS FOR MECHANICAL INSTALLATION RECEIVED AND READY TO AWARD AS SOON AS FUNDS BECOME AVAILABLE

B. SILANE-TO-POLYSILICON

- PROCESS DESIGN COMPLETE
- ENGINEERING DESIGN ONGOING

Process Support R&D Summary

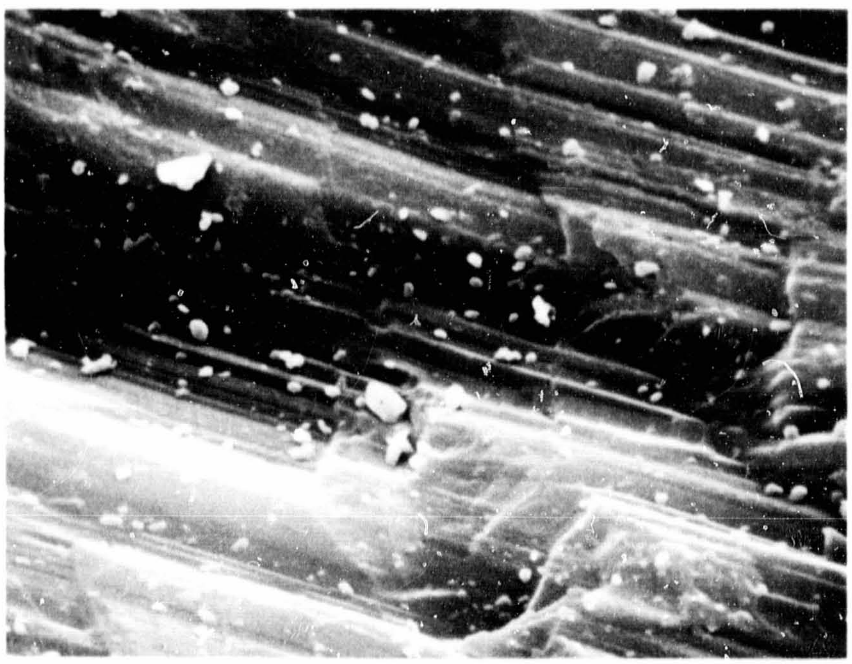
A. Si POWDER MELTING & SHOTTING (KAYEX)

- MELTER/SHOTTER SYSTEM ASSEMBLED
- CHUNK SILICON MELTED AND SHOT PRODUCED AT VARIOUS NOZZLE SIZES
- AT SMALL NOZZLE SIZES (UNDER 1 MM DIA), CONTROL OF SHOT PRODUCTION DEMONSTRATED
- FREE-SPACE Si POWDER SUCCESSFULLY TRANSPORTED TO FEED HOPPER, AND THE POWDER MELTED IN THE MELTER/SHOTTER

B. SILANE PYROLYSIS IN FLUID-BED PDU

- FLUID-BED PDU ASSEMBLED
- SERIES OF BED FLUIDIZATION AND HEATING TESTS WITH NITROGEN AND HYDROGEN SUCCESSFULLY COMPLETED
- 10 TO 21 PERCENT SILANE IN HYDROGEN SUCCESSFULLY FED TO HOT SILICON SEED BED
- DENSE POLYSILICON COATING ON SEED PARTICLES OBTAINED
- FURTHER TESTING STOPPED DUE TO FUNDING RECISION

SEM photomicrograph showing a random selection of Sample No.1 particles. This view shows particles' vivid edges, with high definition of surface characteristics. 50 X.



SEM view of a random particle from Sample No.1. The surface appears to be relatively bare, with the exception of some surface debris. 5000 X.

SEM photomicrograph showing a random selection of Sample No.2 particles. The particles in this view exhibit coated surfaces and well-rounded edges. 50 X.

SEM view of a random particle from Sample No.2. Heavy silicon deposition is apparent on this random-particle surface. 5000 X.

POLYCRYSTALLINE SILICON

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

TECHNOLOGY	REPORT DATE
POLYCRYSTALLINE SILICON	JULY 15, 1981 18TH PIM
APPROACH HYDROCHLORINATION OF METALLURGICAL GRADE SILICON TOGETHER WITH SILICON TETRACHLORIDE AND HYDROGEN TO FORM TRICHLOROSILANE FOR PRODUCING SILICON **CONTRACTOR** MASSACHUSETTS INSTITUTE OF TECHNOLOGY **GOALS** TO SUPPORT THE UNION CARBIDE SILANE-TO-SILICON PROCESS BY CONDUCTING EXPERIMENTAL AND THEORETICAL STUDIES, ● ESTABLISH FUNDAMENTAL UNDERSTANDING OF HYDROCHLORINATION OF METALLURGICAL GRADE SILICON IN TERMS OF REACTION KINETICS AND ROLE OF CATALYST ● OPTIMIZE THE REACTION CONDITION FOR THE HYDROCHLORINATION STEP	**STATUS** COMPLETED JPL CONTRACT NO. 955 382 (MARCH 31, 1979 - APRIL 1, 1981) I REACTION KINETICS MEASUREMENT ● TEMPERATURE ● PRESSURE ● $H_2/SiCl_4$ FEED RATIO ● COPPER CATALYST CONCENTRATION ● PARTICLE SIZE DISTRIBUTION ● EFFECT OF IMPURITIES IN SILICON II MASS LIFE STUDY ● LONG SILICON MASS BED LIFE III CORROSION STUDY ● NO CORROSION OF THE METAL REACTOR ● STABLE SILICIDE PROTECTIVE FILM FORMED AT THE REACTOR WALL IV FINAL REPORT ● ISSUED

Composition of Fines Elutriated From The Hydrochlorination Reactor

ELEMENT	% IN ELUTRIATED FINES	% IN M.G. SILICON
IRON	8.02	0.7
ALUMINUM	0.82	0.45
CALCIUM	1.19	0.05
MANGANESE	0.71	0.06
NICKEL	0.15	0.01
CHROMIUM	0.16	0.01
CHLORINE	7.49	NONE
SILICON (BALANCE)	81.46	98.7

Corrosion Test for Incoloy 800H

CONDITION: 500°C, 300 PSIG, $H_2/SiCl_4 = 2.0$

DURATION: 238 HOURS

SAMPLE WEIGHT	BEFORE =	53.195 G.
	AFTER =	53.520 G.
	GAIN =	0.325 G.

TOTAL SURFACE AREA = 120 CM^2

ASSUMING DEPOSITED MATERIAL IS SILICON

SI FILM OF ABOUT 11.6 MICRONS THICK

THUS, NO SIGNIFICANT AMOUNTS OF CORROSION OCCURS INSIDE THE REACTOR IN VIEW OF THE WEIGHT GAIN BY THE SAMPLE

Effect of Atmospheric Corrosion

SCALE BROKE OFF AFTER EXPOSURE TO AIR AND MOISTURE

TOTAL SURFACE AREA OF TEST SAMPLE = 27 CM^2

SAMPLE WEIGHT: BEFORE	=	12.4026 G.
AFTER	=	12.1445 G.
LOSS	=	0.2581 G.
SI FILM WEIGHT	≈	0.0732 G.
NET LOSS OF METAL	=	0.1849 G.

DENSITY OF INCOLOY ≃ 8.0 G/C.C.
LOSS OF BASE METAL ≃ 8.6 MICRONS

- EVIDENCE OF SI PENETRATION INTO THE BASE METAL TO FORM A SILICIDE PROTECTIVE FILM OF ABOUT 20 MICRONS THICK
- PREVIOUS CORROSION RESULTS APPEAR DUE TO ATMOSPHERIC CORROSION AND NOT DUE TO THE REACTION ITSELF

Summary of Progress

- REACTION RATE AT 500 PSIG, 500°C REINFORCES THE UNION CARBIDE ENGINEERING DESIGN
- COPPER CATALYST INCREASES REACTION RATE BY 100%
- REACTION RATE INDEPENDENT OF Si PARTICLE SIZE
- IMPURITIES IN M.G. SILICON INCREASE REACTION RATE
- LONG MASS LIFE MEANS REACTION CAN BE RUN FOR LONG PERIODS OF TIME WITH NO INTERRUPTION
- CORROSION OF THE METAL REACTOR IS NOT A PROBLEM
- INCOLOY 800 IS A GOOD CHOICE AS THE MATERIAL OF CONSTRUCTION OF THE HYDROCHLORINATION REACTOR

POLYCRYSTALLINE SILICON

SOLARELECTRONICS, INC.

<table>
<tr><td>TECHNOLOGY
POLYCRYSTALLINE SILICON</td><td>REPORT DATE
JULY 15, 1981 18TH PIM</td></tr>
<tr><td>APPROACH
HYDROCHLORINATION OF METALLURGICAL GRADE SILICON TOGETHER WITH SILICON TETRACHLORIDE AND HYDROGEN TO FORM TRICHLOROSILANE FOR PRODUCING SILICON
CONTRACTOR
SOLARELECTRONICS, INC.

GOALS
TO CONTINUE THE HYDROCHLORINATION STUDY IN SUPPORTING THE UNION CARBIDE EPSDU, SILANE-TO-SILICON PROCESS
● COLLECT ENGINEERING DATA FOR SCALE-UP
● QUALITY CONTROL - ANALYSE FOR ORGANIC AND INORGANIC IMPURITIES
● SELECT THE MOST SUITABLE MATERIAL OF CONSTRUCTION FOR THE REACTOR
● INCREASE PROCESS EFFICIENCY AND REDUCE COST</td><td>STATUS JUST STARTED
JPL CONTRACT NO. 956 061
(JULY 1981 - JULY 1982)

PLANNED ACTIVITIES:
● TWO INCH-DIAMETER AND FOUR INCH-DIAMETER HYDROCHLORINATION REACTORS
● REACTION KINETICS MEASUREMENTS
● CORROSION MEASUREMENTS ON VARIOUS CONVENTIONAL METAL ALLOYS
● FLUIDIZATION MECHANICS - STATIC-BED VERSUS FLUIDIZED-BED DESIGN
● WASTE DISPOSAL - WITH BY-PRODUCT HCL RECYCLE TO THE HYDROCHLORINATION REACTOR</td></tr>
</table>

I REFINE ENGINEERING DATA FOR SCALE-UP

- OPTIMIZE PROCESS PARAMETER - 2 INCH REACTOR, 500 PSIG, 500°C
- FLUIDIZATION MECHANICS - 4 INCH REACTOR, MERITS OF A FIXED-BED OR A FLUIDIZED-BED REACTOR DESIGN
- MAXIMIZE RAW MATERIAL UTILIZATION - RECYCLE BY-PRODUCT WASTE STREAM,E.G., HCL TO THE HYDROCHLORINATION REACTOR
- QUALITY CONTROL - ANALYSE ORGANIC AND INORGANIC IMPURITIES IN THE CHLOROSILANE PRODUCTS

II CORROSION STUDY

- MECHANISM OF CORROSION
- SCREEN MATERIAL OF CONSTRUCTION FOR THE REACTOR
- SELECT THE MOST SUITABLE MATERIAL OF CONSTRUCTION FOR THE HYDROCHLORINATION REACTOR ON A COST-EFFECTIVE BASIS

POLYCRYSTALLINE SILICON

HEMLOCK SEMICONDUCTOR CORP.

TECHNOLOGY	REPORT DATE
POLYCRYSTALLINE SILICON	JULY, 1981
APPROACH CHEMICAL VAPOR DEPOSITION OF SILICON FROM DICHLOROSILANE (DCS) **CONTRACTOR** HEMLOCK SEMICONDUCTOR CORPORATION **GOALS** • DEMONSTRATE PROCESS FEASIBILITY • ESTABLISH TECHNICAL READINESS BY OPERATION OF EPSDU SIZED TO ABOUT 150-MT/YR • SILICON PRICE OF LESS THAN #20/KG (1980$, 1000-MT/YR, 20% ROI) • DEFINE PROCESS ECONOMICS	**STATUS** • DCS-PDU CONSTRUCTION COMPLETED • INTERMEDIATE REACTOR/FEED SYSTEM CONSTRUCTED AND TESTED • PDU START-UP COMPLETE • PRELIMINARY INTERMEDIATE REACTOR DATA IN GENERAL AGREEMENT WITH EXPERIMENTAL REACTOR DATA • SILICON PURITY FROM DCS OR REDISTRIBUTED TCS EXCELLENT (ZONE REFINING, SOLAR CELLS)

Price Projection (1980 $, 1000 MT/yr, 20% ROI)

ASSUMPTIONS:

HIGH PURITY POLYCRYSTALLINE SILICON PRODUCT

DICHLOROSILANE PRODUCTION VIA TRICHLOROSILANE REDISTRIBUTION

HYDROGENATION OF $SiCl_4$ AS DEMONSTRATED BY UNION CARBIDE CORPORATION

40% CONVERSION OF DICHLOROSILANE INTO SILICON

PROJECTION:

PRODUCT PRICE: < $20/KG (INCLUDES 20% ROI)

Silicon Production by Dichlorosilane Decomposition

$$SiH_2CL_2+H_2 \longrightarrow Si+H_2,\ HCL,\ SiH_2CL_2,\ SiHCL_3,\ SiCL_4$$

DICHLOROSILANE PRODUCTION

(CATALYZED REDISTRIBUTION OF TRICHLOROSILANE)

$$2\ SiHCL_3 \rightleftharpoons SiH_2CL_2+SiCL_4$$

TRICHLOROSILANE PRODUCTION

(HYDROGENATION OF SILICON TETRACHLORIDE)

$$SiCL_4+H_2+Si_{MG} \longrightarrow SiHCL_3+H_2+SiCL_4$$

Reactor Explosion Test Results

- DEFLAGRATION ONLY IN TEST WITH H_2/DCS/AIR AT 27/3/70 MOLE %.
-

PARAMETER	CALCULATED	OBSERVED TEST 1	OBSERVED TEST 2
JAR BURST PRESSURE	33	30	20
INNER VESSEL	77	80	50
COMBUSTION MODE	DEFLAGRATION PROBABLE		
HEATSHIELD		DAMAGED	NO DAMAGE

- CALCULATED VALUES FOR JAR EXPLOSIONS ARE AN ACCEPTABLE APPROACH TO EXPLOSION CONTAINMENT EVALUATIONS.

Intermediate Reactor Evaluation

RESULTS:

- REACTOR SCALE-UP IS REASONABLE
- WALL DEPOSITION IS A POTENTIAL PROBLEM
- DECOMPOSITION PERFORMANCE

ROD DIA. MM (DCS SEGMENT)	SI DEPOSITED GM/HR/CM	CONVERSION MOLE %	POWER USAGE KWH/KG	NOTE
GOAL	2.0	40	60	
38-52	1.6	41	101	A
34-48	1.6	35	88	
61-70	2.6	33	74	
52-60	1.3	27	136	

NOTE:

A STARTING CONDITION FOR RUNS AFTER PDU START-UP

QUESTIONS:

- ARE ENTIRE RUNS WITH DCS POSSIBLE
- CAN GOALS BE MET WHEN ENTIRE RUNS ARE MADE

PDU Objectives

- DCS PRODUCTION 70 LB/HR
- REDISTRIBUTION CONVERSION >10%; TEMPERATURE AND RESIDENCE TIME TO ACHIEVE THIS
- PRESSURE DROP VS. VELOCITY IN CATALYST BED
- CATALYST LIFE >90% ORIGINAL CAPACITY AFTER 2 MONTHS OPERATION AT CAPACITY
- DETERMINE IF CATALYST MIGRATION OCCURS

PDU Start-Up Summary

- OPERATIONAL JUNE 1 WITH DCS FEED TO A DECOMPOSITION REACTOR
- NO SIGNIFICANT PROBLEMS; SEVERAL MINOR LEAKS (VALVE STEMS, SCREWED CONNECTIONS, ETC.)
- CONTROL SCHEME WORKS FINE; INSTRUMENT ADJUSTMENTS MADE TO FINE TUNE
- ROUTINE, RELIABLE OPERATION AT UP TO 47 LB/HR DCS PRODUCTION
- REDISTRIBUTION REACTOR CONVERSION OF 10.7% DCS, BASED ON STC IN STILL BOTTOMS

Decomposition Goals

- MAKE RATE 2.0 G/H/CM
- CONVERSION EFFICIENCY 40%+
- POWER CONSUMPTION <60 KWH/KG
- RUN TIME 100H+

Comparison of Intermediate-Size(1) And Experimental(2) Reactor Data

RUN NO.	ROD DIAMETER MM	SILICON DEPOSITED $GH^{-1}CM^{-1}$	CONVERSION MOLE %	POWER CONSUMPTION KWH/KG
324-409-2(1)	34-48	1.56	35.2	88
324-410-2(1)	38-52	1.67	41.1	101
394-055-6(2)	35-42	1.66	32.8	74
394-056-4(2)	36-43	1.52	30	92

Comparison of DCS and TCS Data For Intermediate–Size Reactor

Feed Type	Silicon Deposited (TCS=1)	Conversion (TCS=1)	Power Consumption (TCS=1)
DCS	1.95	2.22	Ø.76
DCS	2.23	2.11	Ø.55
All DCS	2.Ø3	2.19	Ø.7Ø

Results

	Parameter	Objective	Achieved
•	Make Rate	2 G/H/CM	1.6-2.0 G/H/CM
•	Conversion Efficiency	>40	37%
•	Power Consumption	<60 KWH/KG	80-100 KWH/KG
•	Run Time	100H	40-80H
•	Good Rod Surface	✓	✓
•	No Vapor Phase Nucleation	✓	✓

EPSDU Objectives

- PRODUCE DICHLOROSILANE FROM REDISTRIBUTION OF TRICHLOROSILANE
- PURIFY DICHLOROSILANE
- PRODUCE HIGH PURITY POLYCRYSTALLINE SILICON FROM DICHLOROSILANE
- RECOVER REACTOR VENT PRODUCTS
- OPERATE ON SCALE OF 100-200 TONNE SILICON/YR.

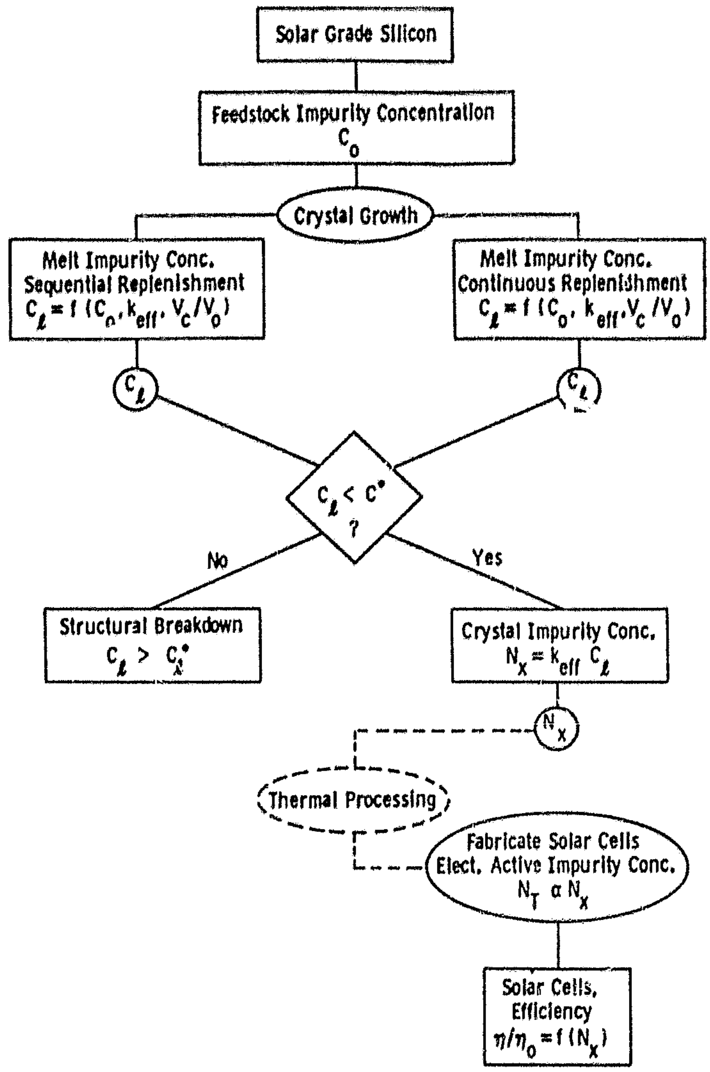
Problems and Concerns

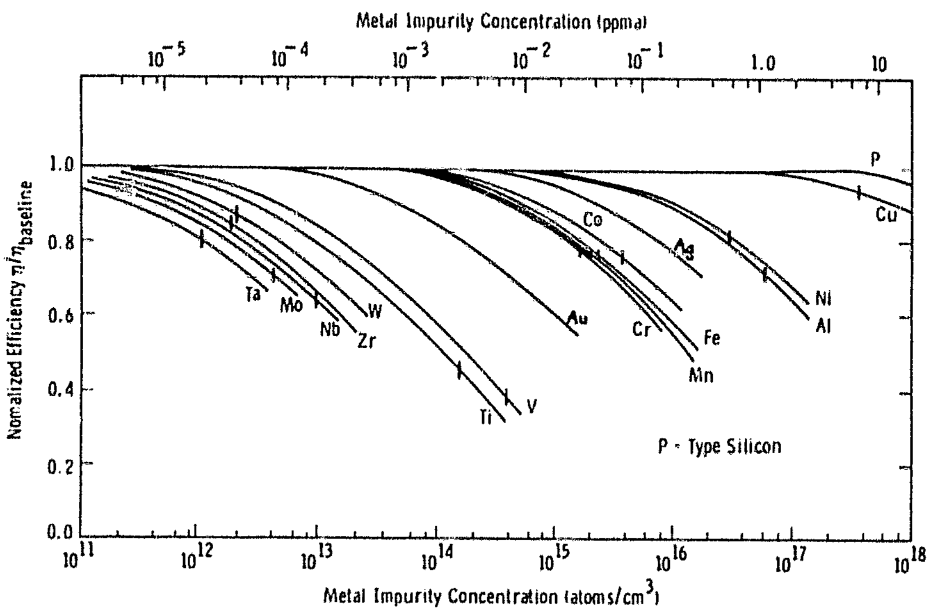
- ACHIEVING 40 PERCENT CONVERSION EFFICIENCY
- ECONOMICS OF HYDROGENATION PROCESS
- EPSDU TIMETABLE

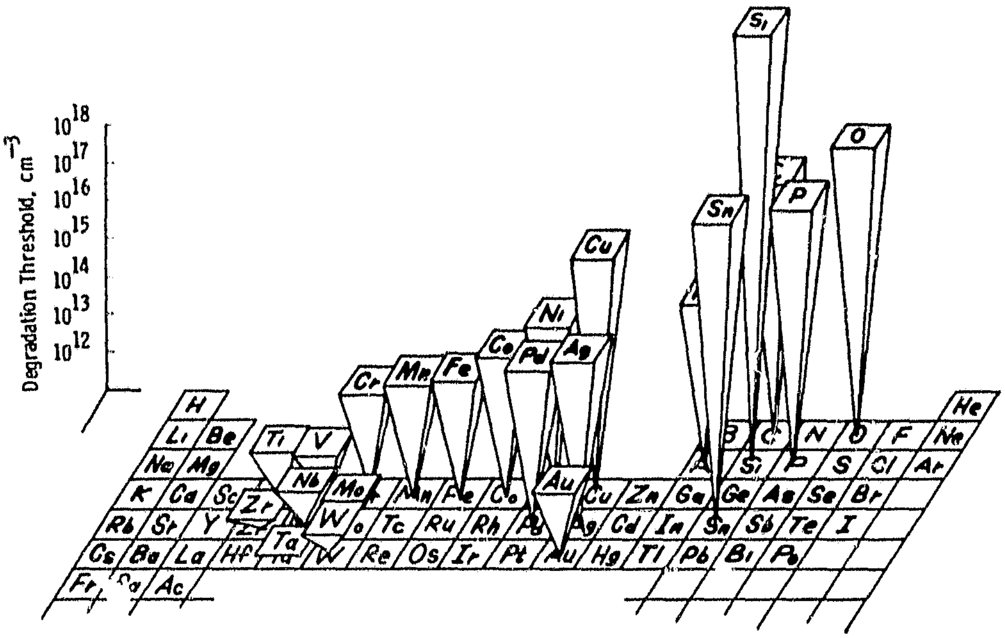
IMPURITY EFFECTS IN SILICON

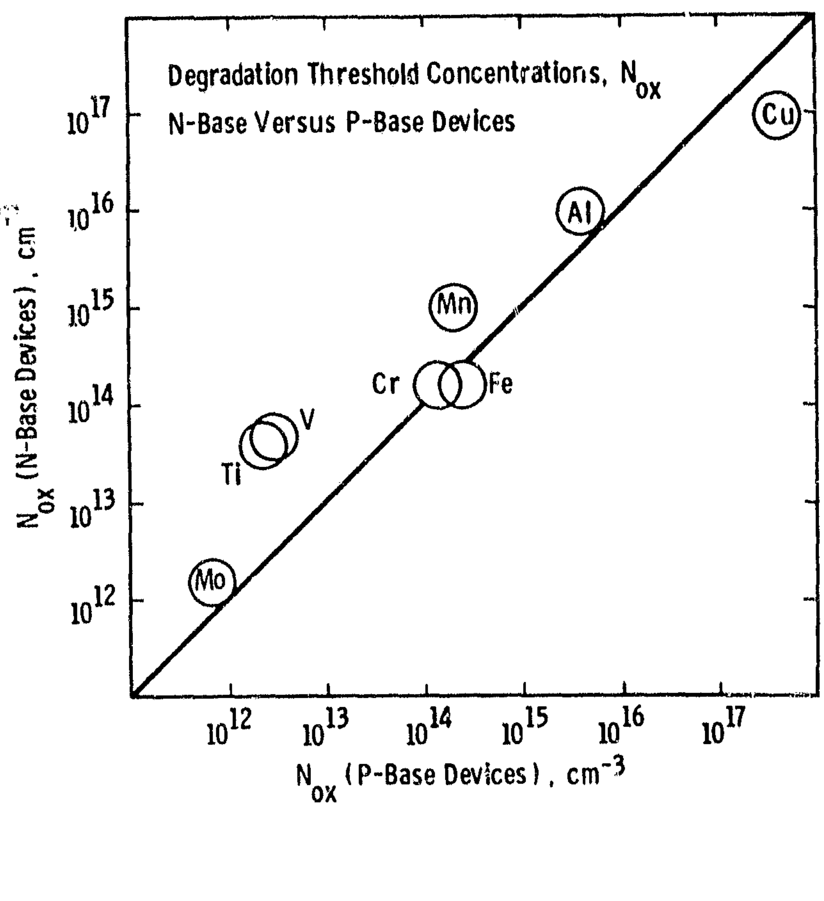
WESTINGHOUSE ELECTRIC CORP.

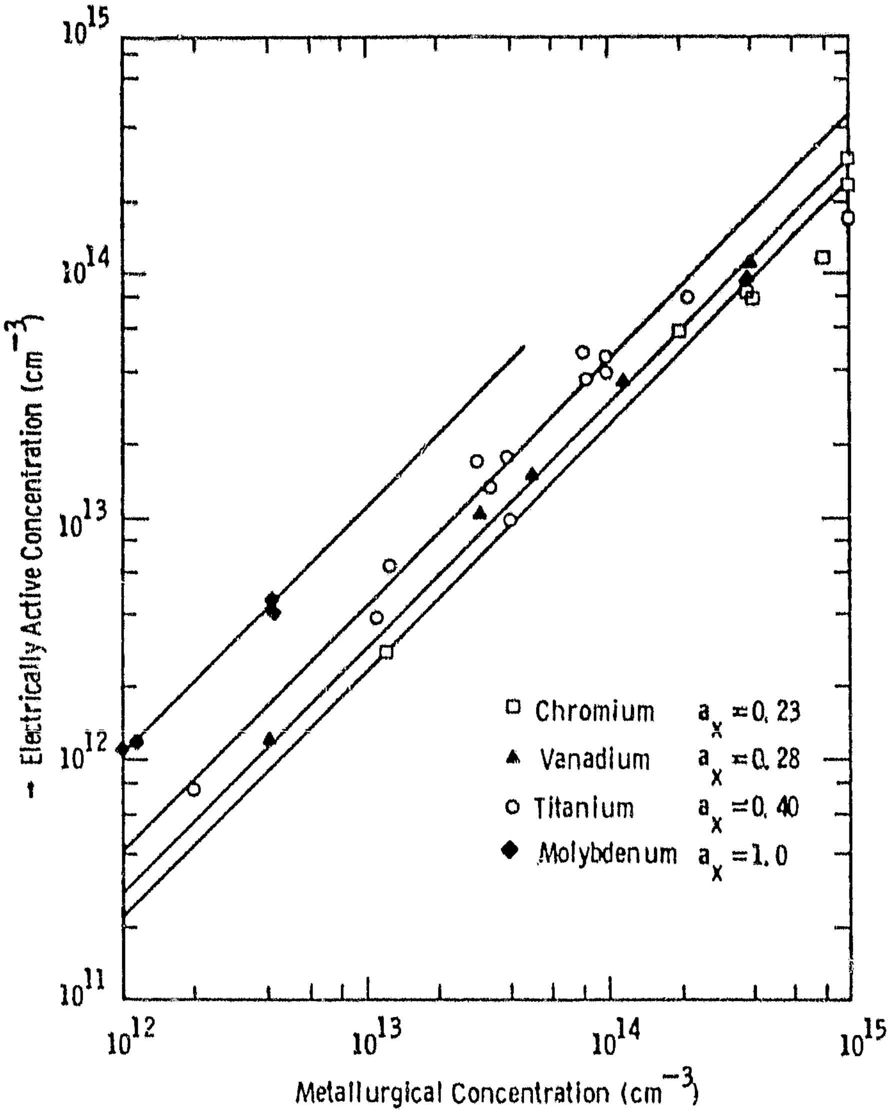
Technology Impurity effects in silicon	**Report Date** 7/15/81
Approach Analysis of silicon material and solar cells with controlled impurity additions **Contractor** Westinghouse Electric Corp., R&D Center	**Status** Phase IV experimental program is now completed. Final report preparation is underway **Recent Results:** • Impurity sensitivity of high efficiency cells reduced in thinner devices • Ar implant damage gettering raises efficiency of Ti-doped cells but not as much as HCl or $POCl_3$ alone • D for impurities calculated from crystal breakdown data lie in range 1 to 4 × 10^{-4} cm^2/sec • Cr electrical activity reduced ten fold in grain boundaries vs. bulk
Phase IV **Goals** Evaluate impurity effects in: • High efficiency cells • Experimental silicon material • Cells subjected to processing e.g. gettering • Cells treated to simulate long term behavior	


Solar Grade Silicon
Feedstock Impurity Concentration C_0
Crystal Growth
Melt Impurity Conc. Sequential Replenishment $C_\ell = f(C_0, k_{eff}, V_c/V_0)$
Melt Impurity Conc. Continuous Replenishment $C_\ell = f(C_0, k_{eff}, V_c/V_0)$
C_ℓ
C_ℓ
$C_\ell < C^*$?
No
Yes
Structural Breakdown $C_\ell > C_\ell^*$
Crystal Impurity Conc. $N_x = k_{eff}\, C_\ell$
N_x
Thermal Processing
Fabricate Solar Cells Elect. Active Impurity Conc. $N_T \propto N_x$
Solar Cells, Efficiency $\eta/\eta_0 = f(N_x)$


Metal Impurity Concentration (ppma)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1.0
10
Normalized Efficiency $\eta/\eta_{baseline}$
1.0
0.8
0.6
0.4
0.2
0.0
P
Cu
Co
Ag
Ni
Al
Ta
Mo
Nb
W
Zr
Au
Cr
Fe
Mn
Ti
V
P - Type Silicon
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
Metal Impurity Concentration (atoms/cm^3)


Degradation Threshold, cm-3
10^18
10^17
10^16
10^15
10^14
10^13
10^12


Degradation Threshold Concentrations, Nox
N-Base Versus P-Base Devices
Nox (N-Base Devices), cm-3
Nox (P-Base Devices), cm-3
Cu
Al
Mn
Cr
Fe
V
Ti
Mo
10^12
10^13
10^14
10^15
10^16
10^17



10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
Electrically Active Concentration (cm^{-3})
10^{12}
10^{13}
10^{14}
10^{15}
Metallurgical Concentration (cm^{-3})
Chromium $a_x = 0.23$
Vanadium $a_x = 0.28$
Titanium $a_x = 0.40$
Molybdenum $a_x = 1.0$

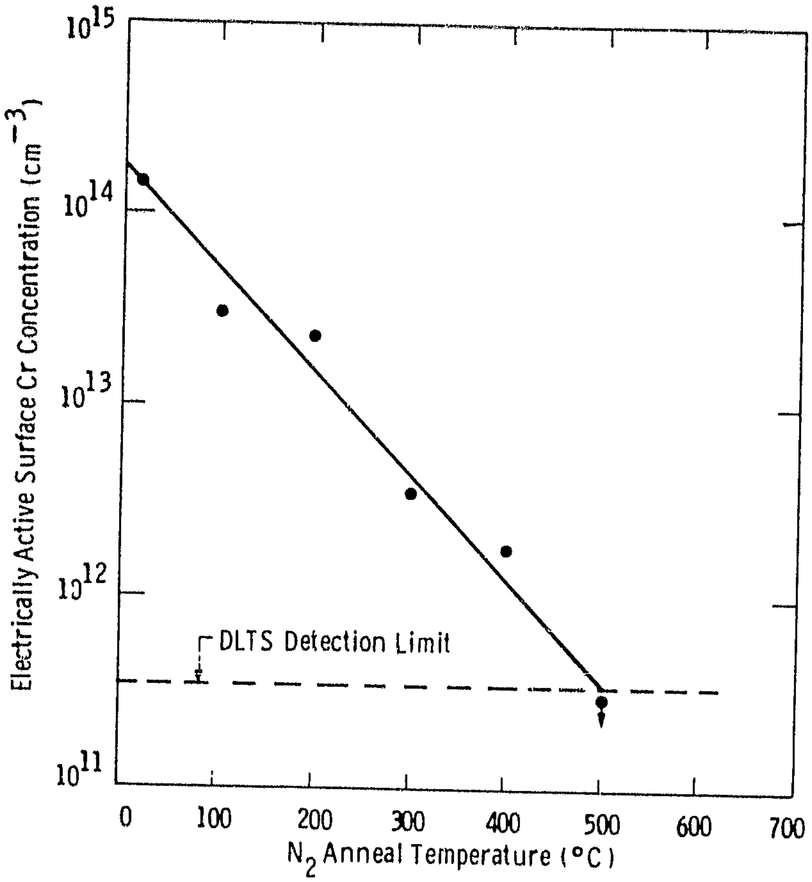
Impurity Concentrations in Multiple–Doped Ingots

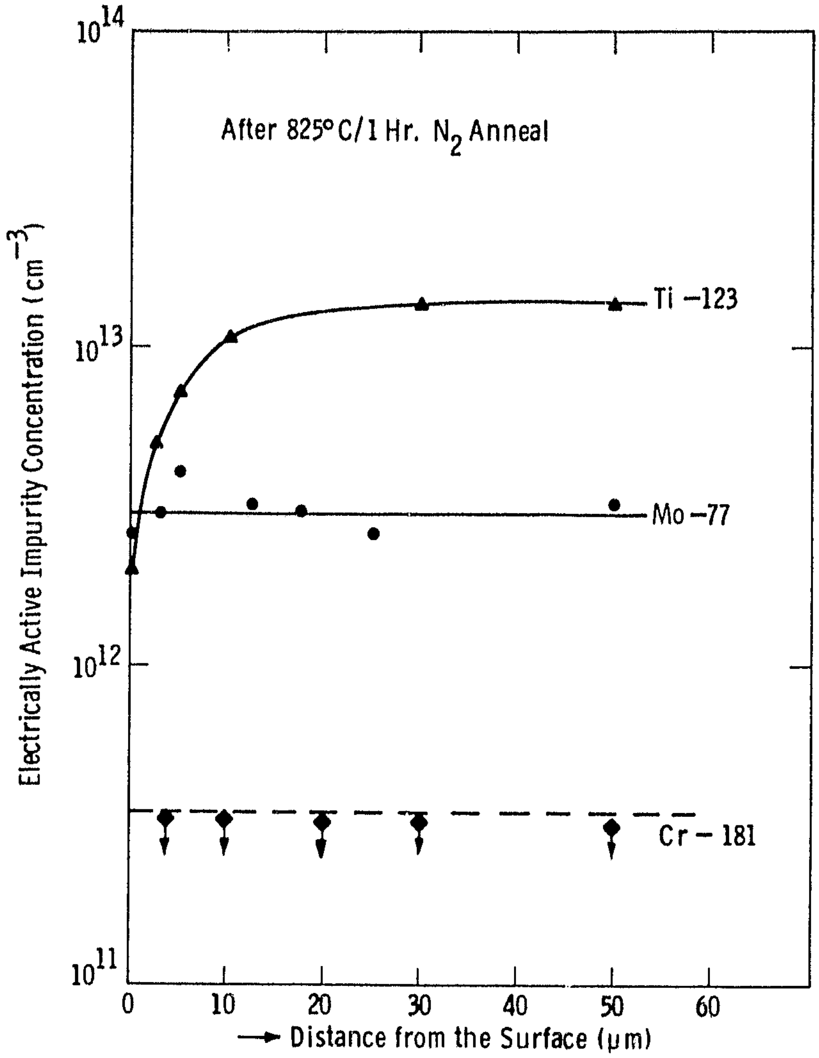
Ingot ID	Trap Levels eV	Expected Trap Concentration (cm^{-3})	Trap Concentration Measured By DLTS (cm^{-3})
158/N-Ti/V/Cr	$E_c - 0.26$ – Ti	2.0×10^{13}	1.9×10^{13}
	$E_c - 0.22$ – V	1.4×10^{13}	1.4×10^{13}
	$E_c - 0.46$ – V	1.4×10^{13}	1.4×10^{13}
061-Cr/Ti	$E_V + 0.31$ – Cr	2.3×10^{13}	3.4×10^{13}
	$E_V + 0.30$ – Ti	4.4×10^{12}	4.1×10^{12}
157/N-Ti/V	$E_c - 0.26$ – Ti	3.2×10^{13}	4.8×10^{13}
	$E_c - 0.22$ – V	3.4×10^{13}	3.7×10^{13}
	$E_c - 0.46$ – V	3.4×10^{13}	3.7×10^{13}
104-Ti/Cu	$E_V + 0.30$ – Ti	5.6×10^{13}	3.6×10^{13}
111-V/Cu	$E_V + 0.42$ – V	8.4×10^{13}	6.2×10^{13}
141-Mo/Cu	$E_V + 0.30$ – Mo	4.2×10^{12}	4.2×10^{12}

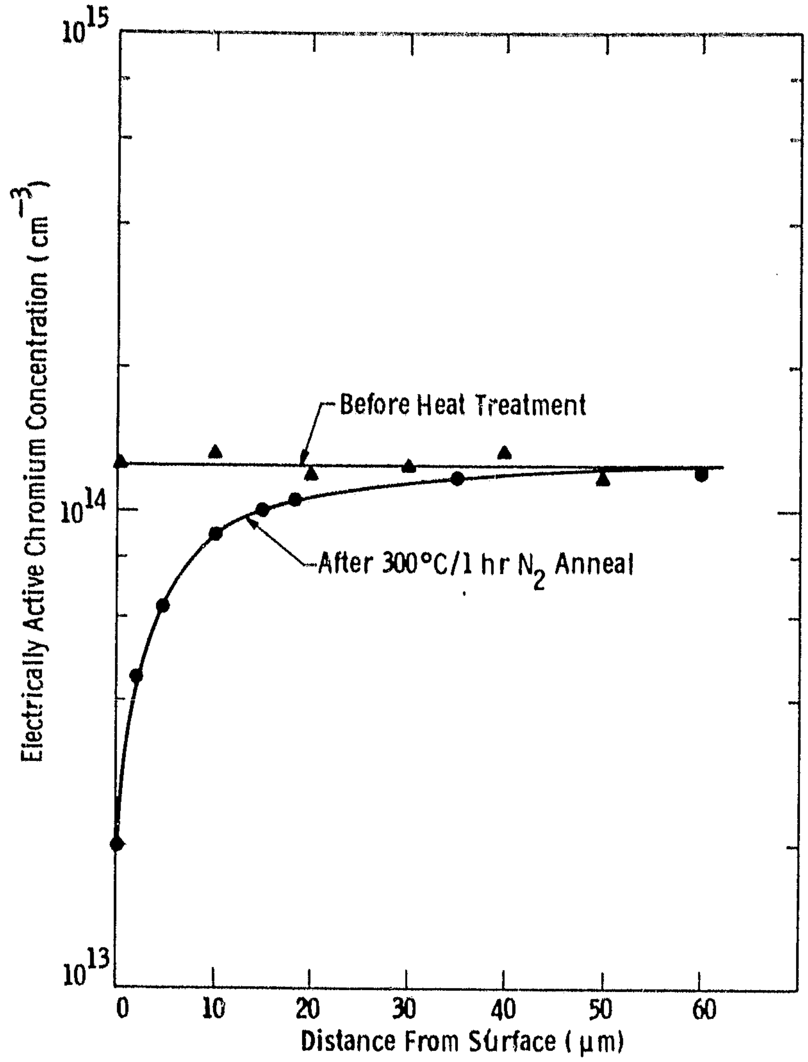
Gettering of Impurities

Gettering appears to be diffusion controlled and is therefore most effective for fast diffusing impurities.

IMPURITY	DIFFUSION CONSTANT(900 C)
Copper	10^{-6}
Iron	$6\ 10^{-6}$
Chromium	10^{-7}
Silver	$2\ 10^{-10}$
Vanadium	$8\ 10^{-10}$
Titanium	$2\ 10^{-11}$
Molybdenum	$< 10^{-14}$
Tungsten	$< 10^{-14}$


Electrically Active Surface Cr Concentration (cm^{-3})
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
DLTS Detection Limit
0
100
200
300
400
500
600
700
N_2 Anneal Temperature (°C)


After 825°C/1 Hr. N2 Anneal
Electrically Active Impurity Concentration (cm⁻³)
10^14
10^13
10^12
10^11
Ti –123
Mo –77
Cr – 181
0
10
20
30
40
50
60
Distance from the Surface (μm)

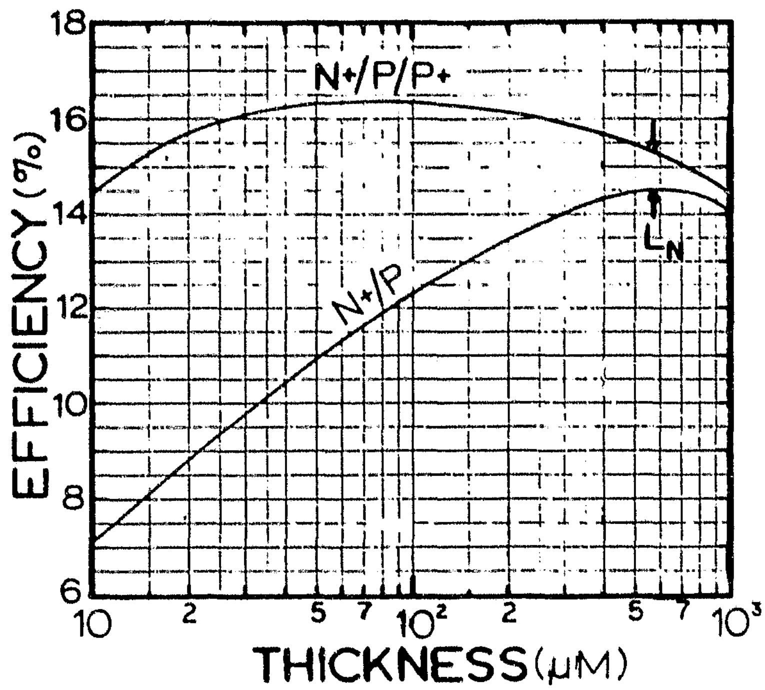


10^{15}
10^{14}
10^{13}
Electrically Active Chromium Concentration (cm^{-3})
Before Heat Treatment
After 300°C/1 hr N_2 Anneal
0
10
20
30
40
50
60
Distance From Surface (μm)

IMPURITY EFFECTS IN SILICON SOLAR CELLS

C. T. SAH ASSOCIATES

TECHNOLOGY	REPORT DATE
IMPURITY EFFECTS IN SILICON SOLAR CELLS	81/07/16
APPROACH ANALYSIS OF THE EFFECTS OF CELL THICKNESS AND DEFECTIVE BACK-SURFACE-FIELD (BSF) JUNCTION IN IMPURITY-DOPED CELLS. **CONTRACTOR** C. T. SAH ASSOCIATES **GOALS** o DETERMINE THE OPTIMUM CELL THICKNESS AND ITS IMPURITY DEPENDENCES. o DETERMINE THE OPEN-CIRCUIT VOLTAGE DEGRADATION DUE TO DEFECTIVE BSF JUNCTION. o EXPERIMENTAL VERIFICATION OF THIN CELL PERFORMANCE.	**STATUS** o DESIGN CALCULATIONS FOR OPTIMUM CELL THICKNESS OF HIGH-EFFICIENCY (17% AM1) IMPURITY-DOPED (ZN) BSF CELLS COMPLETED. o EFFECTS OF PERIMENTER SHUNTS ACROSS THE BSF JUNCTION ON OPEN-CIRCUIT VOLTAGE V_{OC} AS A FUNCTION OF CELL SIZE, THICKNESS AND BASE MINORITY CARRIER DIFFUSION LENGTH ANALYZED. o EFFECTS OF RANDOM BULK SHUNTS ACROSS THE BSF JUNCTION ON V_{OC} ANALYZED. o COMPARISON OF ANALYSIS WITH EXPERIMENTAL ZINC-DOPED THIN (100 UM) CELLS STARTED.



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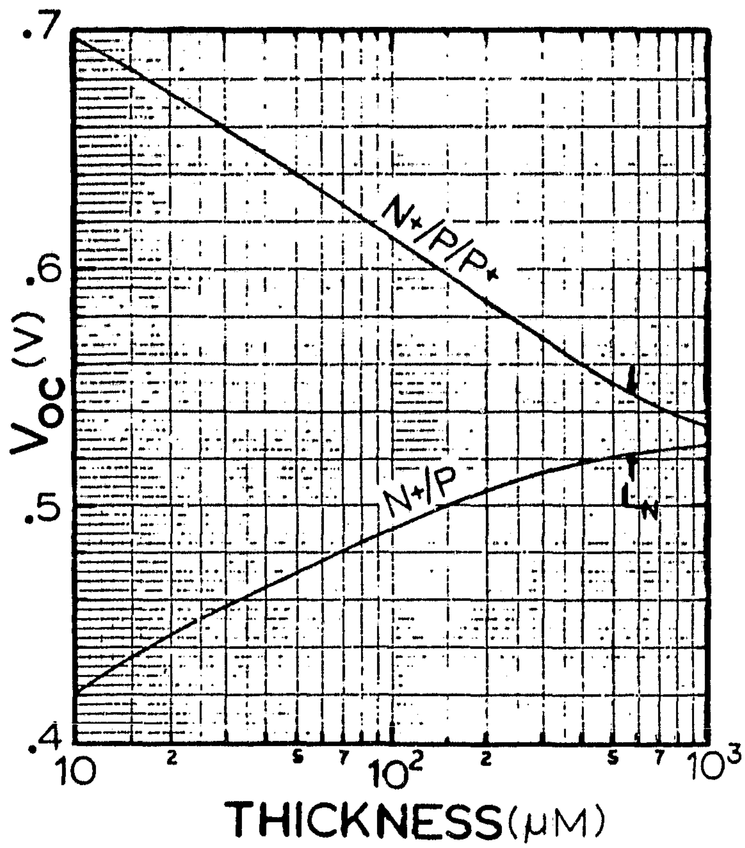
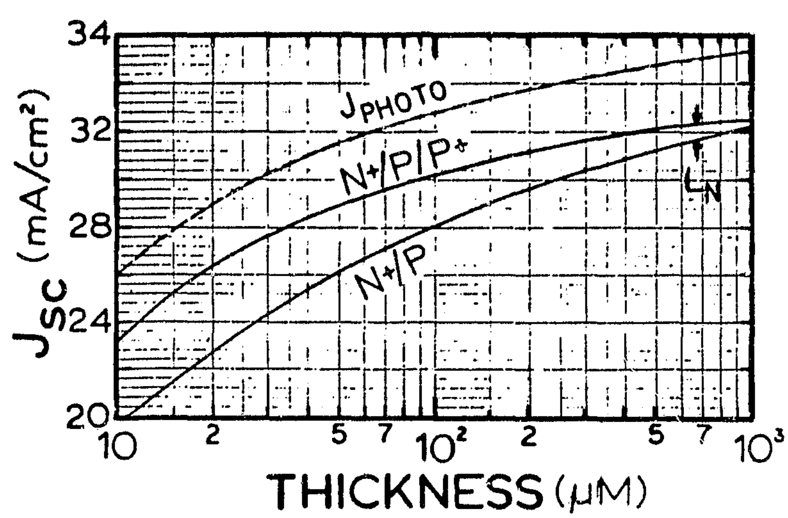
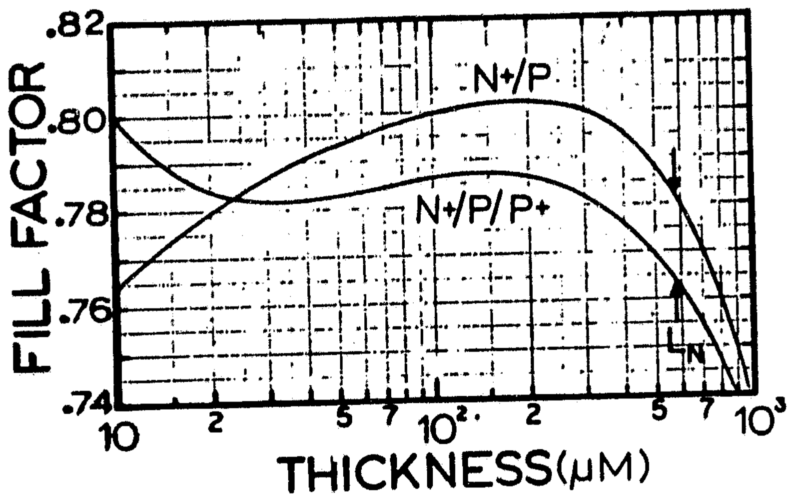






FLUIDIZED–BED REACTOR PROGRAM

JET PROPULSION LABORATORY

- OBJECTIVE
  - EXPERIMENTAL AND THEORETICAL STUDY OF EFFECTS OF OPERATION PARAMETERS ON CHARACTERISTICS OF FBR IN SILANE SYSTEM
- CHARACTERISTICS TO BE STUDIED
  - RATE AND TYPE OF PARTICLE GROWTH
  - YIELDS
  - FINES FORMATION
  - BED AGGLOMERATION
- EXPERIMENTAL VARIABLES
  - SILANE CONCENTRATION
  - TEMPERATURE
  - U/U_{mf}
  - DISTRIBUTOR PLATE DESIGN
  - FBR SIZE

Results From 2-in.-Dia FBR

- RATE AND TYPE OF PARTICLE GROWTH
  - RATE - 0.39 μm/min AT 12% SILANE AND 700°C
    - 0.81 μm/min AT 60 - 100% SILANE AND 700°C
  - TYPE - DENSE, COHERENT FROM 10 TO 100% SILANE AT TEMPERATURE > 600°C

- YIELDS
  - SILANE TO SILICON CONVERSION - 96 TO 100% AT TEMPERATURE ABOVE 650°C
  - OVERALL YIELD ~ 90%

- FINES FORMATION
  - INCREASE WITH TEMPERATURE AND SILANE CONCENTRATION
  - LESS THAN 10% FOR 650°C < TEMPERATURE < 800°C AND 10% $\leq$ SILANE $\leq$ 100%

- BED AGGLOMERATION
  - INSENSITIVE TO DISTRIBUTOR PLATES USED SO FAR
  - PRIMARILY DEPENDENT ON U/U_{mf}
    - $U/U_{mf} > 3$ - CLOG-FREE
    - SUGGESTED OPERATION AT $U/U_{mf} \sim 5$

Present FBR Program

- COMPLETE DETERMINATION OF OPERATIONAL WINDOW BY EXTENDING PARAMETRIC STUDY OF 2-inch FBR

- APPLIED R&D PROGRAM - 6" FBR
  - DESIGN COMPLETED
  - FABRICATION UNDERWAY
  - STUDY OF REACTOR CHARACTERISTICS AS FUNCTION OF OPERATION VARIABLES
  - COLLABORATION WITH OREGON STATE UNIVERSITY

SILANE–TO–MOLTEN–SILICON (SMS) PROGRAM

JET PROPULSION LABORATORY

OBJECTIVE:

EXPERIMENTAL STUDY TO DETERMINE CONDITIONS NEEDED TO PRODUCE MOLTEN SILICON FROM SILANE IN A SINGLE-STAGE PROCESS

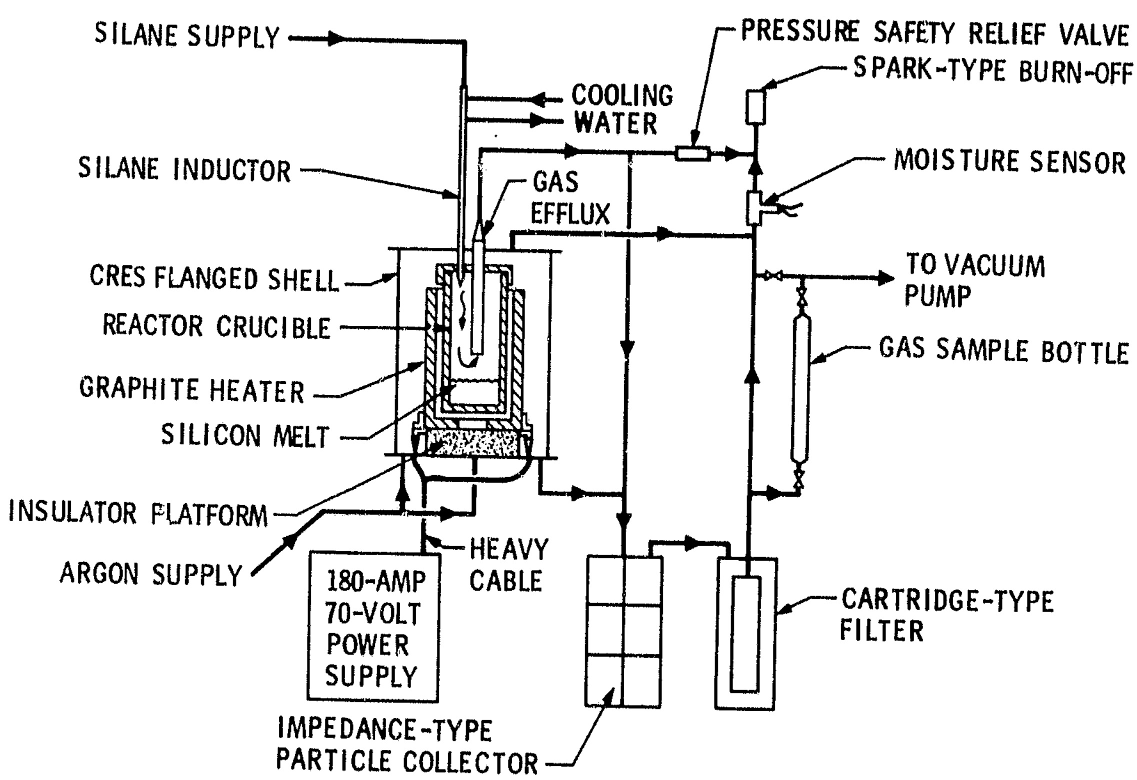
PROBLEMS TO BE SOLVED:

- PLUGGING OF SILANE INLET
- EFFLUX OF SILICON POWDER
- CONVERSION TO MOLTEN SILICON
- NON-CONTAMINATING, LONG-LIFE REACTOR MATERIAL

EXPERIMENTAL VARIABLES:

- CONCENTRATION
- FLOW RATE
- TEMPERATURE
- REACTOR DESIGN AND MATERIALS

SMS Converter System



TECHNOLOGY DEVELOPMENT AREA

Large-Area Silicon Sheet Task

J. K. Liu, Chairman

SHAPED-SHEET TECHNOLOGY

Mobil Tyco Solar Energy Corp. (EFG)

A three-ribbon (each 10 cm wide) growth run was made in March with Machine No. 16. Total growth run time was approximately 6.5 h and the total of 10-cm-wide ribbon produced was ≈33.8 m. Cartridge No. 1 produced 10.2 m of ribbon at an average growth rate of ≈3.6 cm/min; Cartridge No. 2 produced ≈12.3 m at an average growth rate of ≈3.2 cm/min, and Cartridge No. 3 produced ≈10.6 m at an average growth rate of ≈3.2 cm/min. Two single-cartridge runs were made in April to check the automatic width-control system and the ribbon-pull-system guidance. A 10-cm-wide ribbon with a uniform thickness of 6 mils was grown at a speed of 4 cm/min by refining the die-top temperature profile and improving the die design. Two runs were made in June, continuing the evaluation of the effect on material quality by CO_2 ambient manipulation. A gas-tight ribbon seal was made. It controls the gas ambient in the cartridge to achieve repeatable ambient growth conditions. Cartridges longer than 10 cm for Machine No. 16 have been designed.

Face heaters for Machine No. 17 have been installed and the hollow-die design has been completed. Several runs were made with the single ribbon machine to evaluate face heaters and a hollow die. Six runs were made in June 1981 to test growth rates. A growth of 4.1 cm/min was achieved by using the cold shoe with a modified die and thermal configuration. Four runs were made in July to evaluate new linear cooling plates used to flatten the thermal profile in the cartridge.

Several runs were made with Machine No. 18 without using the cold shoe. The main-zone temperature in this machine was found to be nonuniform. New die-face heaters were installed to improve the growth rate and ribbon thickness uniformity. Three runs were made in June to evaluate a two-piece die and a modified thermal shield between the afterheater and the die top; both worked well. Six runs were made with Machine No. 18 in July. No cold shoe was used. Two-piece dies and a special shield were used. Ribbons produced were thinner at the center. A critical design review of new multiple ribbon growth Machine No. 21 was completed in April and the block diagram and line sketches of the machine were provided to JPL. Its cartridges will be longer than those of Machine No. 16. The heating power supply for Machine No. 21 has been delivered; fabrication of the main zone of the furnace of Machine No. 21 has been completed.

Westinghouse Electric Corp. (Web)

A Reticon diode array was evaluated for dendrite thickness and/or web-width control. Westinghouse hopes that the dendrite thickness will change slowly enough that an operator can maintain control manually and that the ribbon width can be handled passively. It is believed, however, that the array

sensor system can now be considered a back-up if required. Programmed start-up of growth has been demonstrated successfully in a series of trials.

Mechanical design has been completed for the growth chamber and chamber top and bottom plates. The frame has been redesigned to accommodate the modified chamber. A ribbon take-up reel material, a molded high-density polyurethane, has been settled on.

Continuous width control, a significant milestone achievement, has been demonstrated. Westinghouse has grown 5 m of ribbon at 10.1 mm width deviation. Successful control is attributed to a combination of fine melt-temperature control and heat-shield design. Westinghouse will use ribbon-width drift as a long-term temperature drift indication and will control both with a closed-loop system. This is expected to obviate dendrite thickness monitoring.

The new melt-replenishment crucibles are 33% longer than the original design and are working well. The new automatic melt-level controller has been tested on the ribbon machine and is performing as designed.

The improved melt-level-control and melt-replenishment circuitry received its initial test, actually pulling web, and performed well. The programmed growth start-up has now been successfully interfaced with a second puller. Switch-over from automatic start-up to melt-level-control and constant width control still is manual, but routine. Longer crucibles, which were designed to allow the growth of wider ribbon, were operated on a trial basis growing 1-in.-wide ribbon. No problems were observed.

In the area of process analysis, stress modeling has essentially been completed. Temperature profile modeling has been initiated. Stress data from production runs correlates well with the modeling results.

The first iteration of a mathematical model explaining stress-induced buckling of web is now completed. It has been verified against known lid and shield configurations in use in the laboratory today. Heretofore, shield design has evolved empirically. New configurations will now be designed, based on previous growth experience and on the model.

Experimental growth runs to identify a thermal geometry suitable for the high-speed growth of low-stress ribbons continued. Design of a "wide" geometry to allow the growth of >1 in. ribbon is under way. The mechanical design of the ESGU is complete. Mechanical and electrical construction have begun.

INGOT TECHNOLOGY

Kayex Corp. (Advanced Cz)

The ESGU CG6000 puller was run for the first time on March 19. Except for a few minor problems, the machine ran well, producing 13.7-cm-dia 22-kg ingot from a 30-kg melt. The crystal diameter was limited by a misalignment of the pull cable.

Kayex has completed five growth attempts with the new ESGU Czochralski system. These were debugging runs using 14-in.-dia crucibles. For the

most part, the system worked well and some 15-cm-dia zero-dislocation ingot sections have been obtained. Power-line functions and acoustic noise, both from the power supply, originally a cause for concern, now appear to have been solved.

Three crystal-growth runs were made in the Advanced Cz ESGU puller in May. The first yielded an 18-in.-long 18-kg ingot, ≈30% dislocation. The growth rate was low (≈2in./h) due to poor thermal gradients. The second run was made at an increased chamber argon pressure (30 vs 10 torr). Considerably less 'smoke' was observed. Although this is an effective way to achieve better crystals, it is more expensive. The crystal grown was 5.4 in. in diameter, 24 in. long, 20 kg in weight, and was totally zero-dislocation. For the third growth run, a graphite chimney was used to reduce the growth chamber size above the crucible. This was intended to increase the purging effect of lower argon flows (20 torr). The resulting crystal was cleaner than any before it, but was polycrystalline.

The gas chromatograph has been assembled and installed on the ESGU.

Three additional crystal-growth runs were made in the advanced Cz ESGU puller in June. The first run yielded 15 in. (≈15 kg) of zero-dislocation 6-in.-dia. ingot: 32 kg were solidified in total from the 35-kg melt at a growth rate of 1.29 kg/h. The purpose of the second run was to set up and test the melt sensor for a planned 150-kg run. Twenty-five kg of zero-dislocation single-crystal were grown from the 32-kg melt. An attempt to extend this run to 150 kg failed because the virgin poly used to recharge the crucible proved to be contaminated as received from the supplier. The third run was a successful attempt to grow 150 kg from a single crucible in the ESGU unit. Approximately 30% of the silicon pulled was zero-D. Kayex believes that the progressive loss of structure of the ingots as the run proceeded and the more frequent icing of silicon on the crucible walls can be attributed directly to crucible degradation. This may be a serious problem; it will be addressed by Kayex as the program proceeds.

After the successful 150-kg growth run in June, the machine was shut down for retrofitting of the Kayex-developed microprocessor hardware for process automation. The interfacing with the microprocessor (dubbed AGL, for Automatic Grower Logic, by Kayex) will be completed and testing will begin soon.

Crystal Systems, Inc. (HEM)

In March CSI grew a 35-kg HEM ingot in 18 h (growth rate of 1.9 kg/h). This is the fastest growth rate of their recent six-ingot growth series. Typical growth rates had been ≈1 kg/h. To achieve the faster growth rate the furnace temperature was made lower than usual; as a result the top of the ingot experienced some freezing problems.

In May CSI grew a [illegible] x 30-cm, 35-kg ingot that meets the specifications set forth for this demonstration.

Using a new vacuum pump and trap on the HEM crystal growth system, CSI grew the fifth 35 kg ingot in a series of six for JPL in June. The ingot solidified in 21 h and had a total cycle time of approximately 52 h. The

material is very shiny. Some silicon carbide particles can be seen on the surface of the ingot. A new 2-in. heat exchanger will be used in growing the next ingot in order to increase the solidification rate by increasing the heat extraction rate.

The final 35-kg ingot required under the current contract has been grown. The solidification time for the ingot was 40 hours and the total cycle time was 70 hours.

In an ongoing JPL effort to characterize HEM ingots, CSI's material was found to contain a high density of dislocations and of silicon carbide precipitates. To reduce the number of SiC particles, CSI replaced the trap on the mechanical pump with one of a different design. The function of the trap is to prevent the backstreaming of oil into the furnace during the growth cycle. The ingot grown after the change has a bright metallic shiny surface and no large SiC particles were detected visually.

Semix Inc. (Semicrystalline Casting)

A program review was held at Semix on March 3 and 4. Considerable insight was gained into the technology underlying the Semix program. Differences in solar-cell performance measurements have been resolved. Present performance of 10 x 10-cm cells was found to range up to 11% AM1.

The first quarterly report was reviewed and approved in May for public release. The second quarterly report was released in July; the third quarterly report has been returned to Semix for revisions.

Solar cells and wafers have been received by JPL on schedule. Two 10 x 10 x 15 cm ingots were received by JPL in June.

The detailed ESGU implementation plan is expected to be completed by the end of July.

Some Semix wafers have been sent to Applied Solar Energy Corp. (ASEC) for cell fabrication.

A revised technology projection for $.70/watt and a continuation program plan for FY82 and beyond continue under review. Negotiations continue to produce a plan consistent with technology requirements and budget limitations.

Cells manufactured by Applied Solar Energy Corp. (ASEC) using an unsophisticated baseline process gave efficiencies comparable to other polycrystalline sheet materials. Advanced processing methods are being applied by ASEC and Semix to determine material limits.

Differences in predicted SAMIS price for Semix material continue to be reviewed and narrowed.

Silicon Technology Corp. (ID Wafering)

HEM material of 11 x 11-cm cross section was cut by STC with the RD-22 machine. The wafers were 7 mils (175 μm) thick and the kerf was 11 mils (275 μm).

This results in a material utilization of 0.94 m^2/kg (22 wafers/cm). The cutting rate was increased from 1.3 cm/min to 3.8 cm/min with production yields of 98% to 99%. A combination of handling experience and encapsulation of the ingots in epoxy is responsible for this progress.

Crystal Systems, Inc. (FAST)

CSI was able to slice a 10-cm-dia ingot with 99% yield, using a soft Ni plating on a tungsten core wire. The average slicing rate was 3.1 mils/min. This 157-wire pack used wires produced by CSI in-house facilities; it cut 19 slices/cm in its first run. The same wire pack was being reused for a second run.

CSI had two significant accomplishments in April: the first wafering run to slice through a 15-cm-dia ingot successfully, at a cutting rate of 2.0 mils/min, slicing at 19 wafers/cm with a yield of only 20%, and two successive runs slicing 10-cm-dia ingots at 25 wafers/cm. The cutting rate for the first run was 3.6 mils/min; the yield was 34% and the wafer thickness was 8.3 mils with a kerf of 7.7 mils. The yield of the second run was 99.1%, with only two wafers broken out of their largest wire pack yet (224 wires). The average cutting rate for the run was 3.03 mils/min with a wafer thickness of 8.1 mils and kerf loss of 7.9 mils.

CSI continued to slice 15-cm-dia material at 19 wafers/cm and 10-cm-dia material at 25 wafers/cm. All of the 15-cm-dia ingot runs have had very poor yields (as low as 4%). The reason for this is not well understood by CSI. They speculate that if one wafer breaks, the broken pieces become lodged between the wires and the next wafer, tending to cause a domino effect and resulting in a low yield. To eliminate this problem they plan to feed the ingot into the wire pack from the top rather than the bottom and flush broken pieces downward. A 10 x 10-cm section ingot run was completed at 25 wafers/cm with a resultant yield of 46%.

Using a steel-core copper-flashed wire instead of the usual expensive tungsten wire, CSI fabricated a wirepack that successfully sliced through three 4-in.-dia poly Cz ingots. The wirepack was electroplated all around with 45-μm natural diamond. The wires were spaced 19/cm and were baked to eliminate hydrogen embrittlement. The first cut sliced at an average rate of 3.5 mil/min (the goal was 4.1 mil/min) and had a yield of 99.4%. The second run averaged 1.7 mil/min with a 63% yield. Most significant is that the wire-pack was dressed before the third run, which is not normally done. The results of the third run were an average cutting rate of 2.58 mil/min (a substantial increase over the second run) and a yield of 37%. The low yield is attributed to the fact that a bearing in the drive mechanism had to be replaced, leaving the ingot half-sawn for four days while repairs were completed.

Two attempts were made in July to slice 4-in.-square cross-section ingots but were aborted due to alignment problems. A third 4-in.-square cross-section ingot was sliced, resulting in a poor yield of only 19%. An unusual cutting profile was cited by CSI as the reason for the failure.

Two 6-in.-dia ingot wafering runs were aborted, the first due to excessive wire breakage and the second due to diamond pullout in the wire. Efforts to improve the yields are continuing.

LARGE-AREA SILICON SHEET TASK

P. R. Hoffman (MBS)

P. R. Hoffman Division of Norlin Industries completed the first two MBS wafering runs on the new contract in April. These were intended to be baseline runs that would yield slurry for reclamation studies. The Norlin-owned Varian saw was debugged during the runs and run yields were excellent. Details of plans for future runs were reviewed during a visit to Hoffman.

In addition to two sets of three runs each to study the effects of blade-head speed and vertical feed force, two runs were made in May to evaluate various vehicle:grit ratios.

Preliminary design of the wafer lift-off mechanism has been started. The detailed design has not yet been specified.

A series of sawing runs were made to evaluate the effect of varying the vehicle (PC oil):abrasive (SiC) ratio. When all other parameters are standard and held constant, preliminary results indicate that optimum cutting speeds are achieved at a 1-gal-vehicle:2.5-lb-abrasive ratio. Cutting rate fell off gradually on either side of this mix. A limited series of runs with increasing blade pressure showed increasing cutting rates. High blade pressure, a shortened stroke, high blade speed and a 1:4 slurry ratio produced cutting rates greater than twice those seen at standard conditions and 1:25 slurry ratio.

Preliminary used-vehicle recycling experiments were run for the contractor at the Bureau of Mines (Department of the Interior) at Rolla, Missouri. A successful process, possibly scaleable, was identified. It includes centrifuging to reclaim the oil (less filler, identified as diatomaceous earth by Sanborn Associates for the contractor), and heavy-liquid centrifuging to separate the silicon (<1-3 μm particle size) from the SiC, and drying of the sludge product. Initial microscopic examination of the SiC shows no apparent wear of the abrasive particle surface. The oil may be reconstituted by adding diatomaceous earth (lost in the first centrifuging step) or silica flour.

The alternative cutting oils received in June have been evaluated relative to the standard PC oil. Gardoil and Lubrizol, both petroleum- rather than fat-based fluids, appear have advantages over the PC oil. Lubrizol, especially, has price, clean-up and surface-tension advantages. Filtration, rather than centrifugation, is being considered for the oil recycling process because of the high costs of the heavy liquids used in the centrifugation.

MATERIAL EVALUATION

Applied Solar Energy Corp. (Cell Fabrication)

Cells of web material characterized by MRI did not show significant variations in performance. This uniformity was expected, since the MRI study revealed a fairly uniform distribution of defect densities for these samples.

Cells made from EFG ribbon grown with and without ambient CO_2 during the same run (baseline cell process) showed no difference in efficiency, V_{OC} or I_{SC}. Samples from a similar EFG ribbon run that did show significant difference in efficiency have been stripped of metallization and sent for chemical analysis.

HEM ingot No. 41-48 was wafered into horizontal and vertical cross-sections. Cells were fabricated from wafers taken from the top, middle and the bottom of the horizontally cut sections and from a vertical section taken through the center of the ingot. All cells showed signs of shunting on series resistance, partly due to poorly sintered front contacts. However, 30% of the area covered by the wafers was excluded from measurement due to severe shunting. Cell efficiencies and fill factors indicate that only 39% of the top portion of the ingot was usable, showing efficiencies 79% of that of the Cz controls. Microcracks were indicated as a probable cause for the poor initial condition of the ingots, which had chipped and crumbling corners and sides. The material yielding the highest efficiency was from the center, where cells had 91% of the efficiency of the controls, with 67% usable area. The horizontal slice from the bottom yielded cells with 83% usable area. Microprecipitates--apparently SiC; see Crystal System Inc. (HEM above--are still suspected as the cause of the low efficiencies and non-uniform results obtained from the HEM material.

Gettering experiments to improve efficiencies of HEM cells from ingot No. 41-48 are under way. Phosphorus-glass gettering and subsequent surface removal before junction formation is being used.

Solar cells were fabricated on Semix ubiquitous crystallization process (UCP) silicon material. Sixteen 2 x 2-cm cells were cut from each of six wafers to map the response of the material over the entire wafer. Adjacent wafers were kept at JPL for studies to correlate electrical characteristics with structure.

Fabrication of solar cells from UCP silicon with an extra diffusion glass-gettering step revealed that there is no significant difference in efficiencies of cells with and without a gettering step. Diffusion lengths of baseline cells predictably correlated with the short-circuit current.

Cell fabrication from ribbon was held up due to difficulties in obtaining a flat surface on the ribbon.

Material sent to Semix for correlation of their cell fabrication results with those of ASEC did not yield useful data, due to Semix processing problems.

Cornell University (Characterization)

A report has been prepared on work done on RTR material. Cornell researchers observed that one electrically active defect consists of a pair of coherent twins interacting with two stacking faults. Presumably the interaction makes the defect electrically active.

Cornell has done high-resolution lattice imaging of grain boundaries in EFG. They have discovered small precipitates in processed EFG material that did not exist before processing. They have also completed some electron-beam induced-current (EBIC) experiments on silicon-on-ceramics (SOC).

Cornell continues to make progress in the characterization of structural defects in silicon-sheet materials. They have completed EBIC experiments on HEM material. In order to investigate structural defects responsible for the reduction of the EBIC signal, several specimens are being prepared for TEM studies. They also have discovered high-order twin boundaries in some sheet materials using the lattice-image technique.

LARGE-AREA SILICON SHEET TASK

During July, Cornell continued studies of high-order twins and low-angle boundaries using high-resolution TEM.

A program was initiated to study hydrogen-plasma passivation of grain boundaries in EFG materials using conventional hydrogen-plasma generators and Cornell's high-power plasma diode. The latter is a plasma machine that provides a high-current beam of hydrogen ions on the order of several thousand amperes. Under the high current bombardment, the top level of the material is melted and regrown in a hydrogen-rich environment.

Materials Research, Inc. (MRI) (Si Sheet Microstructure)

Approximately 450 cm^2 of Si material was delivered to MRI for structural characterization using a Quantimet 720. Seventy 2 x 2-cm wafers of HEM Si, 60 cm^2 of as-grown EFG ribbon and 20 cm^2 of cell-processed EFG ribbon were included. Four levels of step etching were to be performed on the solar-cell processed EFG material. The material was grown under varying atmospheres, e.g., CO^2 on or off, argon low or high volume. The cells were made at ASEC. MRI has reported the results of their analysis to JPL.

University of Illinois (Silicon Surface Study)

A contract was signed between the University of Illinois and JPL to support a study of surface-softening effects on silicon. Silicon will be abraded by a diamond stylus in the presence of various n-alcohols at selected temperatures to determine the mechanism of wear of the silicon surface and to characterize the surface damage. An optimum combination of temperature and coolant (n-alcohol) will be identified. It is hoped that this study will shed some light on the interactions of coolants and silicon surfaces that occur during silicon wafering.

A detailed program plan has been received from UI. Experiments have begun to establish force normal to the surface and speed of rotation baselines for abrasion of p-type single crystal silicon at room temperature to deionized water, acetone and ethanol. Future experiments will involve varying the speed or rotation and abrading the silicon in the presence of mixtures of n-alcohols with water.

IN-HOUSE ACTIVITIES

Crystal Growth

Four directionally solidified silicon ingots produced from in-house growth facilities were sectioned for macrostructure determination. The crucible materials for these ingots were hot-pressed SiC coated with CNTD (a manufacturer's designation) SiC, hot-pressed with Si_3N_4 with CNTD Si_3N_4 coating, and bulk graphite (Run 6A) (nonpurified). Semiconductor-grade Si was melted in the graphite, SiC and one of the Si_3N_4 crucibles. The other Si_3N_4 crucible contained metallurgical-grade Si. Grain size was largest for the Si grown in the SiC crucible. Cracking of both crucible and Si ingot was evident in each of the runs.

Eight Cz ingot growth runs were successfully completed. The purpose of the runs was to grow shaped Cz ingots.

Four square-cross-section crystals were successfully pulled during June 1981. The critical growth parameters to achieve and maintain the square cross section are being defined.

During July 1981, seven (100) silicon single crystals and one 211/211 10° bicrystal were grown. All of the (100) ingots were square and approximately 2 to 4 in. long.

Wafering

The first demonstration run using the restored Varian 686 multiblade slurry (MBS) saw has been completed. A 100-blade pre-pinned 7.5 cm-blade pack with 8-mil (200-μm)-thick steel blades, 0.25-in. (0.65 cm) height and 14-mil (350-μm) spacers was used. The wafered ingot measured approximately 11.5 x 14 x 5 cm and was mounted on a Plexiglas submount. Final wafering yield was ≥80%. The slurry was composed on PC oil with 2 lb/gal of No. 600-grit SiC.

Present activities include jigging the MBS manufacturing saw for a second demonstration run using a recently procured 30-blade pack made up of 8-mil (200-μm) thick by 0.5 in. (1.3-cm)-high blades.

Seven HEM Si wafer samples, wafered by a high-speed Meyer-Burger MBS saw, were received for depth of damage, bow, taper and thickness analysis. Thirty-eight coupons were sectioned out of the wafers for saw-damage study. Saw damage was observed to be nonuniform. Statistically, depth measurements were made from zero to ≈75 μm. Average depth of damage appeared to be in the 8-to-12 μm range, while random surface areas exhibited depth of damage in the 25-to-50 μm range (maximum). Wafer thickness, bow and taper were also measured and reported.

A second demonstration run using the restored MBS Varian 686 manufacturing saw has been completed. Final wafering yield was 88%; only five wafers were broken during the first half of the cut. Cutting rate was ≈1 to ≈2 mils/min. Renovation of the research MBS varian saw is nearing completion. A cutting-feed pressure transducer loop and other types of control instrumentation have been installed. The central sections, 2 x 2 x 4 cm, of four ingots grown by directionally solidified casting have been obtained. These sections are now being sliced into 15-to-20-mil-thick wafers for electrical characterization.

Optimization testing of selected corrosion inhibitors continued for MBS application by using fatigue tests of 1095 high-carbon steel blades in a water solution of corrosion inhibitors. Several concentrations of these selected corrosion inhibitors in water were tested. A 20-h water-base SiC abrasive slurry recirculation simulation run was made to investigate the suspension characteristics of 2 lb SiC to 1 gal water.

First attempts to run the instrumented Varian MBS wafering machine resulted in a gear-box failure. A new gear was ordered. The instrumented Varian multi-blade wafering machine includes all electronic controls and digital force readout (in pounds).

Eight-mil-nominal-diameter Laser Technology, Inc, Super Wire, a candidate for the FAST saw, was studied. Evaluation consisted of tensile-strength testing and scanning electron microscopy (SEM) examination. The Super Wire consists of a high-tensile core material and an electrolyte copper sheath for holding 45 μm diamond. Three tensile pull tests were performed on as-received wire. There was very little scatter in the load value at failure, one indication of uniform quality material. The average failure load was 8.34 lbs. At the nominal 8-mil diameter this corresponds to a tensile strength of about 170 klb/in^2. However, the core diameter measures out at about 5 mil. The tensile strength of the core material is then about 427 klb/in^2.

Material Characterization

Work on the surface-recombination velocity-measurement technique has been completed. Different Si surfaces have been used for measurement. An in-house document is being prepared. Surface passivation experiments will be done soon.

Reasonably good EBIC pictures of Silso and HEM polycrystalline solar cells have been obtained using SEM with electron energy down to 2 KeV. Since the depth penetration range of 2 KeV electrons in Si is about 0.06 μm, the EBIC pictures reflect the lateral distribution of minority carrier diffusion length in the n^+ region. Various differences in contrast among grains were observed, which could be due to the differences in minority carrier diffusion length and/or electron scattering rate among the grains. The lack of EBIC contrast in the intergranular regions could have either or both of two causes: the minority carrier recombination rate in the grains is at least as high as that at the grain boundaries, or the phosphorus diffusion process used to form the n^+ layer has passivated the grain boundaries.

A technique employing temperature dependence measurements of grain-boundary resistance, capacitance and capacitance transients is being developed to study the effects of heat treatments not only on intergranular sites but also on the properties of the material in the vincinity of grain boundary.

EBIC measurements of grain boundaries in the diffused n^+ regions of silicon solar cell continue. Grain boundary lines with line widths larger than 0.5 μm have been observed. Grain boundaries in the diffused region observed by EBIC have line widths that are usually on the order of 1 μm. Some grain boundaries in this region become unobservable. All of the grain boundaries in the base region seem to be electrically active and easily observed. The difference in observability of grain boundaries using EBIC between diffused and base regions can be attributed to the difference in diffusion length.

Several experiments were performed on light-induced transient and static capacitance changes of grain boundaries in bicrystalline samples. The results support the premise that a grain boundary having a suitable potential barrier acts as a minority carrier trap when it is illuminated with weak light. The data also show that the light-induced transient capacitance could be used to measure minority carrier trapping levels at the grain boundary. More experiments and detailed studies are needed to explore the potential of the technique.

Deep-level transient spectroscopy (DLTS) measurements on Si bicrystal samples were performed. Three additional bicrystalline ingots were grown and their properties have been tested. In addition to the bicrystals grown, one run was made to evaluate the chamber contamination level in the Cz puller.

Effects of thermal annealing up to 800°C on grain-boundary barrier heights and intergrain states in bicrystal samples have been studied using temperature dependence measurements of capacitance, conductance and DLTS techniques. Preliminary data indicate that the barrier height and the density of states usually increases with increasing annealing temperature. The data also indicate the existence of some inhomogeneities in the distribution of structural defects along the boundary, which makes explanation of the data difficult.

Experiments to evaluate effects of bias conditions of DLTS spectra of bicrystalline silicon samples are continuing. The purpose of the experiments is to measure the trapping stages in the depletion regions at each side of the grain boundary and to obtain more information about electronic states associated with grain boundaries and their effects on carrier trapping and recombination.

Two sets of Semix square polycrystalline wafers were tested by the four-point twisting method. The 50% fracture probability of Semix poly-wafer is approximately 12 klb/in^2; that of Motorola 3-in.-dia Cz wafers is about 15 $klb/in.^2$ and ASEC 4-in. dia Cz wafers is 20 $klb/in.^2$. This preliminary result indicates that Semic polycrystalline wafers have lower strength than Cz single-crystal wafers.

Oxygen concentration mapping and measurement of the size and density of the SiC precipitates in HEM ingots were done. The dislocation and twin-plane densities were also measured.

A study was made of the preferential crystallographic orientation of small sections of polycrystalline HEM material. All planes found near the sample surface belonged to the zone of crystallographic planes (001)-(111)-(110) with the axis of the zone in the <110> direction. The samples were taken from wafers that were sliced parallel to the ingot's growth direction.

Economic Analysis

Price-sensitivity analysis runs were made for the web process with updated data and modification of some of the subroutines of the SAIPEG program. Using computer programs developed within the Task, analysis was performed on the effect of silicon cost on sheet and module prices.

ID WAFERING

SILICON TECHNOLOGY CORP.

Contract Goals

6-INCH DIAMETER -	17-18 WAFERS/CM (23 MILS T + K)
4-INCH SQUARE 4-INCH ROUND	25 WAFERS/CM (16 MILS T + K)

<u>SLICING METHODS</u>

PLUNGE CUTTING	6" Ø ROUND 4" Ø ROUND 4" SQUARE
ROTATIONAL CUTTING	6" Ø ROUND 4" Ø ROUND

Slicing Results

	KERF	SLICE THICKNESS	WAFERS/CM	CUTTING SPEED	YIELD
6" Ø PLUNGE	13 MILS	12 MILS	16	1.5 IN/MIN	85%
6" Ø ROTARY	11.5 MILS	18 MILS	13	.6 IN/MIN	50%
4" Ø ROATRY	9.5 MILS	9 MILS	21	.8 IN/MIN	85%
4" PLUNGE (TYPE 1)	11 MILS	5 MILS	25	1 IN/MIN	90%
4" PLUNGE (TYPE 2)	10.5 MILS	8-10 MILS	19-21	1 IN/MIN	20-60%

Slicing Influences

1) TYPE OF CRYSTAL
   - SINGLE CRYSTAL ORIENTATION
   - DIFFERENT MANUFACTURERS OF POLY CAST INGOTS
   - STRESS, CRACKS
2) VIBRATION
3) BLADE MOUNT
4) BLADES
5) RECOVERY AND HANDLING

Goals

CRYSTAL SIZE	WAFERS/CM	ADD-ON COST/M^2
10 CM	25	$18
15 CM	18	$14

Recent Achievements

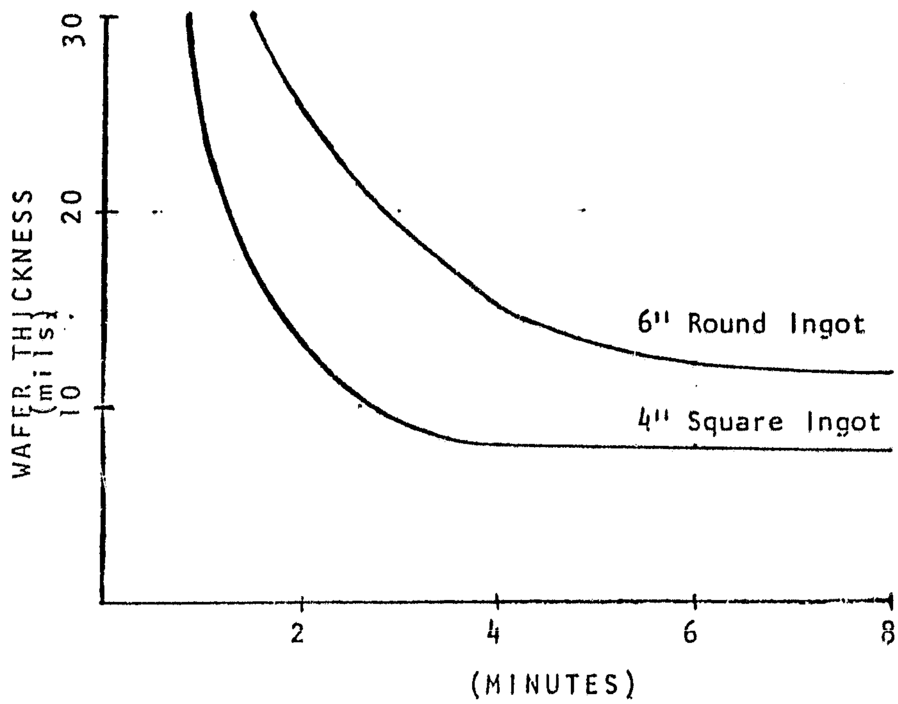
CRYSTAL SIZE	T	K	S	WAFERS/CM	ADD-ON COST/M^2
10 CM	5.5	10.5	1"/MIN	25	42.50
15 CM	12	13	1.5"/MIN	16	25.76

Speed vs Thickness

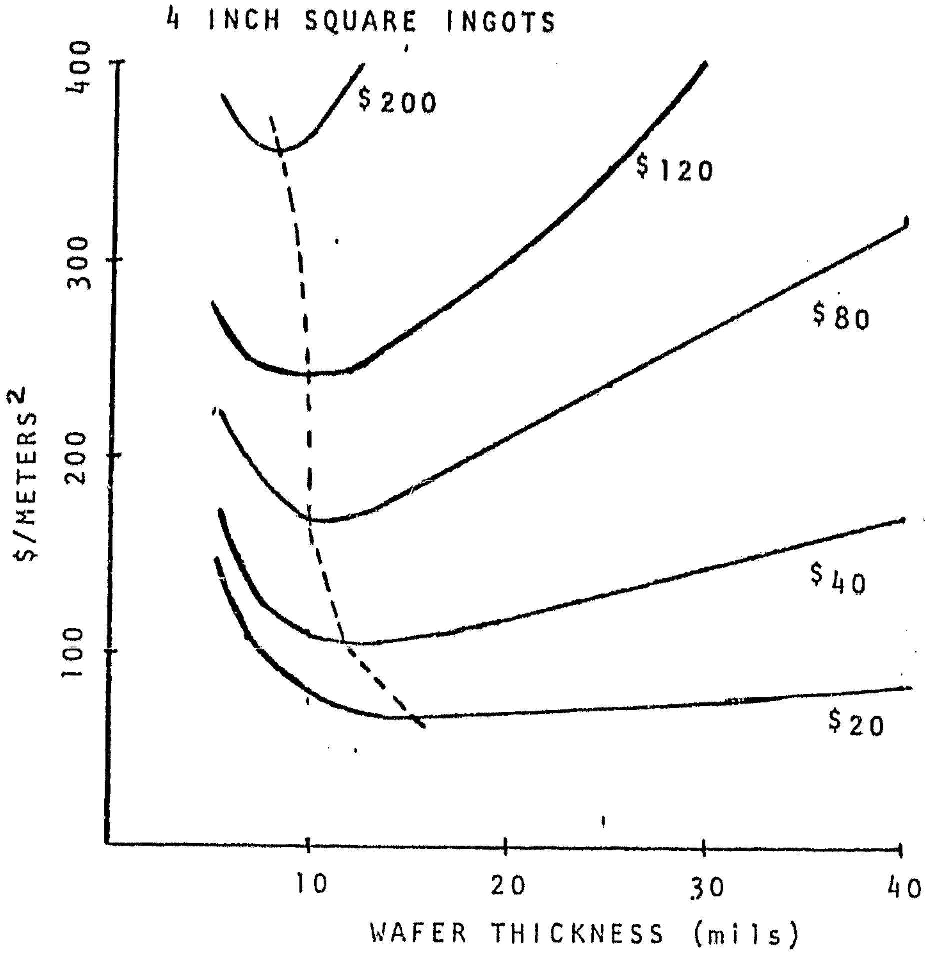
Kerf=11.5 mils	Yield=95%	4" Square Ingots	
Slicing Speed (in/min)	time (min)	Wafer Thickness (mils)	
0.5	40	6	
0.75	8	7	
1.0	4	8	
1.5	2.7	10	
2.0	2	12	
3.0	1.3	18	
4.0	1	25	(Kerf =12.5 mils)
6.0	.7	40	(Kerf =13.5 mils)

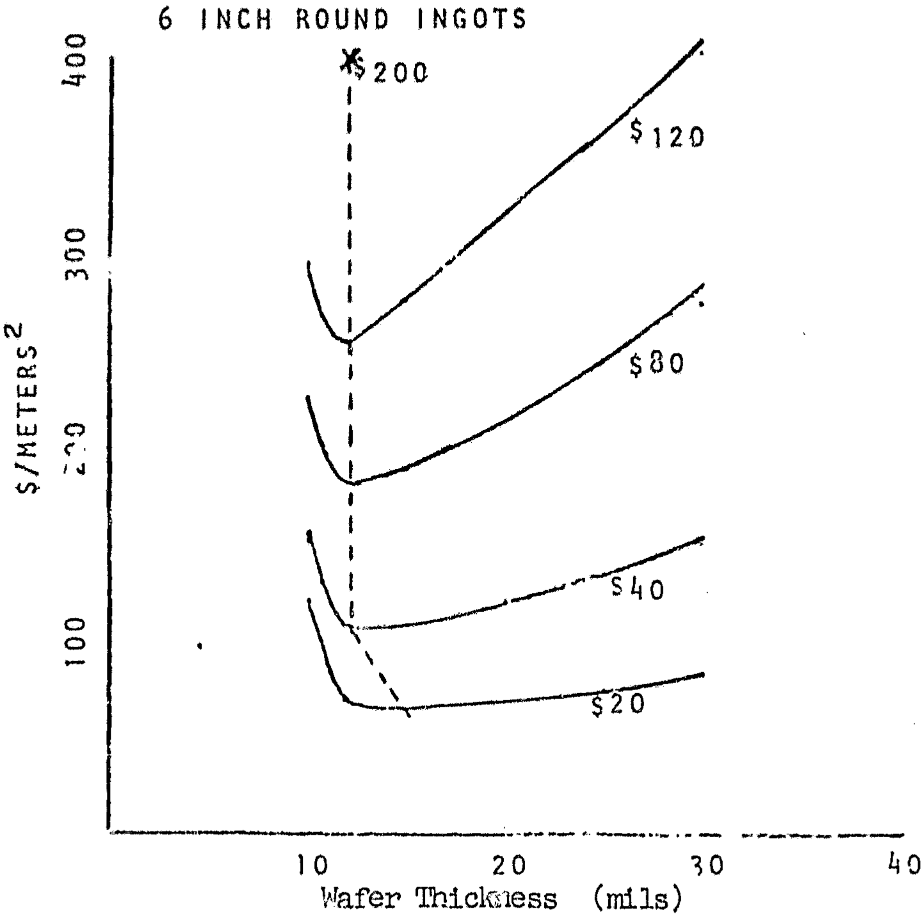
Kerf=13.0 mils	Yield=95%	6" Round Ingots
Slicing Speed (in/min)	time (min)	Wafer Thickness (mils)
0.5	60	10
0.75	12	11
1.5	6	12
2.0	4	15
2.5	3	20
3.0	2	25
4.0	1.5	30
6.0	1	40

Time per Slice vs Wafer Thickness



Total Sheet Cost vs Wafer Thickness at Varying Ingot Cost





The dotted lines represent minimum cost.

Cost Sensitivity Analysis: 10-cm-Square Ingots

COST PARAMETER	VALUE	$\dfrac{\Delta \text{ TOTAL COST} / \text{TOTAL COST}}{\Delta \text{ PARAMETER} / \text{PARAMETER}}$
Yield	.95	-.99
Ingot Cost	$40	.67
Ingot Size	10cm	-.37
Wafer Thickness	12mils	.34
Kerf	11.5mils	.33
Hours/day	20	-.29
Days/year	360	-.29
Slicing Speed	2 inches/min	-.28
Equipment Cost	$40,000.	.13
Labor Cost	$12,500.	.10
Floor Space	84 Sq. Ft.	.06
Blade Cost	$100.	.04
Blade Life	3000	.04
Utility Cost	$1,676.	.01

Total Cost = $\$105.17/\text{Meter}^2$

4-in.-Square Ingots

T = 7 mils

K = 9 mils

S = 4 inches/min

Equipment = $40,000

Floor Space = 84 square feet

Labor rate = $12,500/year - 4.7 shifts per year

10 saws per operator

Utilities + Material = $1,676 per year

20 hours per day

360 days per year

Blade Cost = $50.00

Blade Life = 4,000 wafers

Add-on Cost = $16.33

25 wafers/cm

6-in. Round Crystal

T = 12 mils

K = 10 mils

S = 3 inches/min.

Equipment = $40,000

Floor Space = 84 sq. ft.

Labor rate = $12,500/year, 4.7 shifts/year
10 saws/operator

Utilities + Materials = $1,576/year

20 hours per day

360 days per year

Blade Cost = $80.00

Blade Life = 4,000 wafers

18 Wafers/cm   Add-on Cost = $15.83

Near-Term Development Projects

BLADES -

27 IN. AND 32 IN. BLADES FOR
6 IN. AND 8 IN. INGOTS

4.8 MIL CORES FOR 22 IN. & 27 IN. BLADES

10.5 MIL KERF - 22 IN. BLADES

EQUIPMENT -

27 INCH MACHINE FOR PRODUCTION
- 6 IN. INGOTS
- FULL AUTOMATION
- SQUARE INGOTS
- MICROPROCESSOR CONTROLS

32 INCH EXPERIMENTAL SAW
- 9 INCH CAPACITY

Long-Term Projects

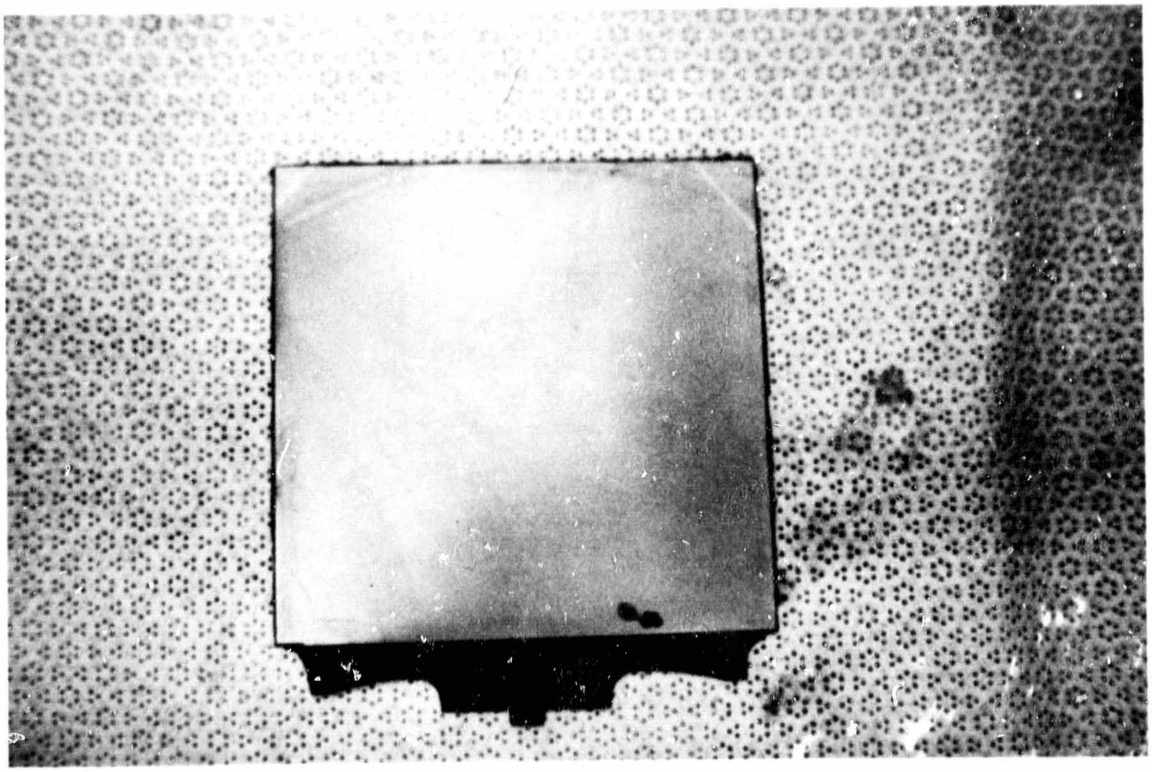
BLADES -

- NEW MATERIALS
- REDUCE CORE TO 3 OR 4 MILS ON 22 IN. AND 27 IN.
- NEW DIAMOND MATRIX

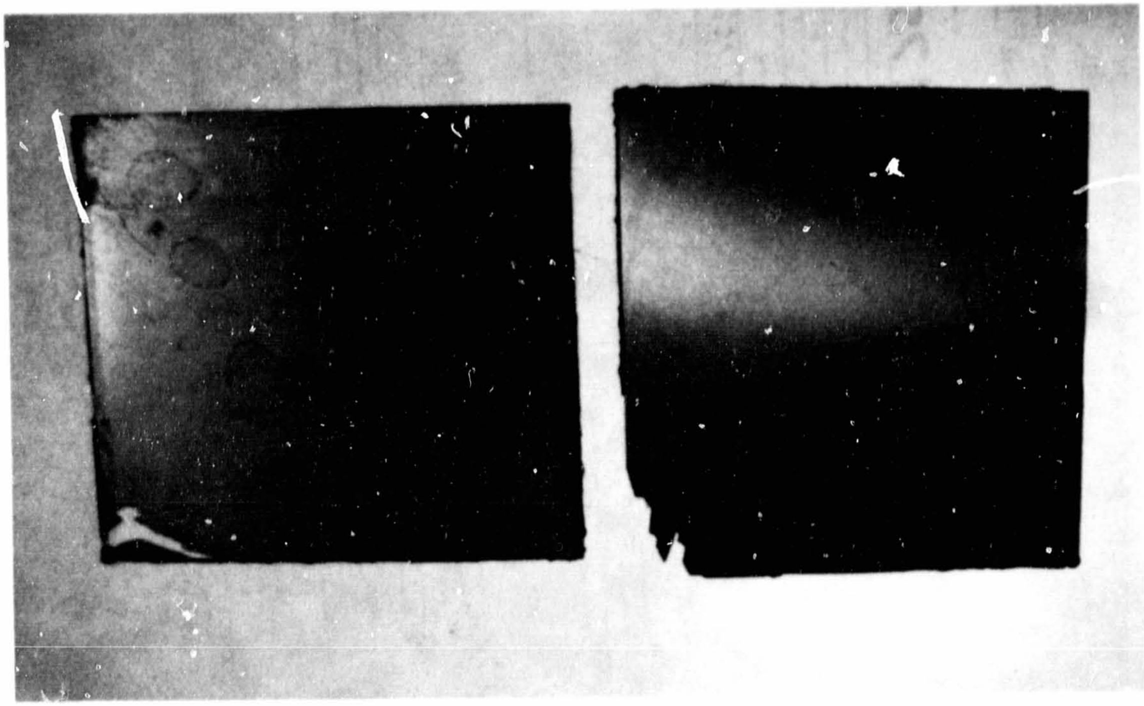
EQUIPMENT -

- LARGE CAPACITY - LOW COST MACHINES FOR PHOTOVOLTAICS
- FULL AUTOMATION WITH FEED-BACK LOOPS.
- CENTRALIZED MONITORING AND CONTROL
- AUTOMATED LINE.

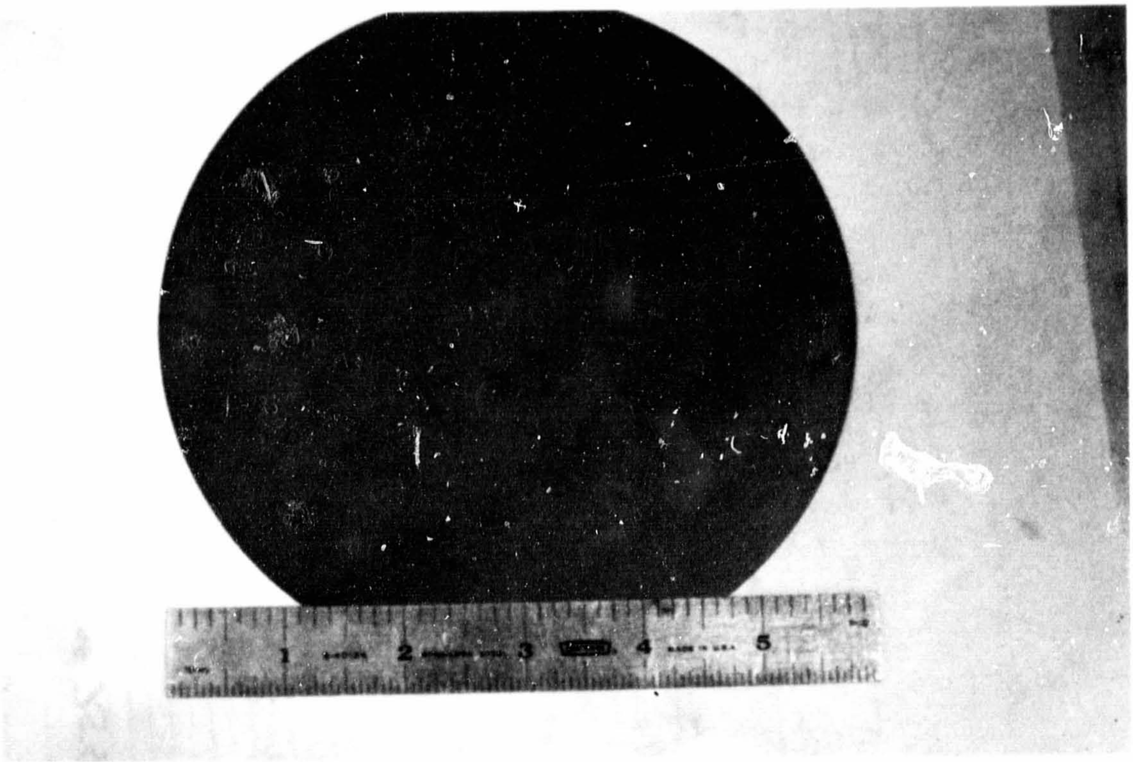
10 X 10 cm HEM Wafer Sliced With STC 22-in. ID Saw



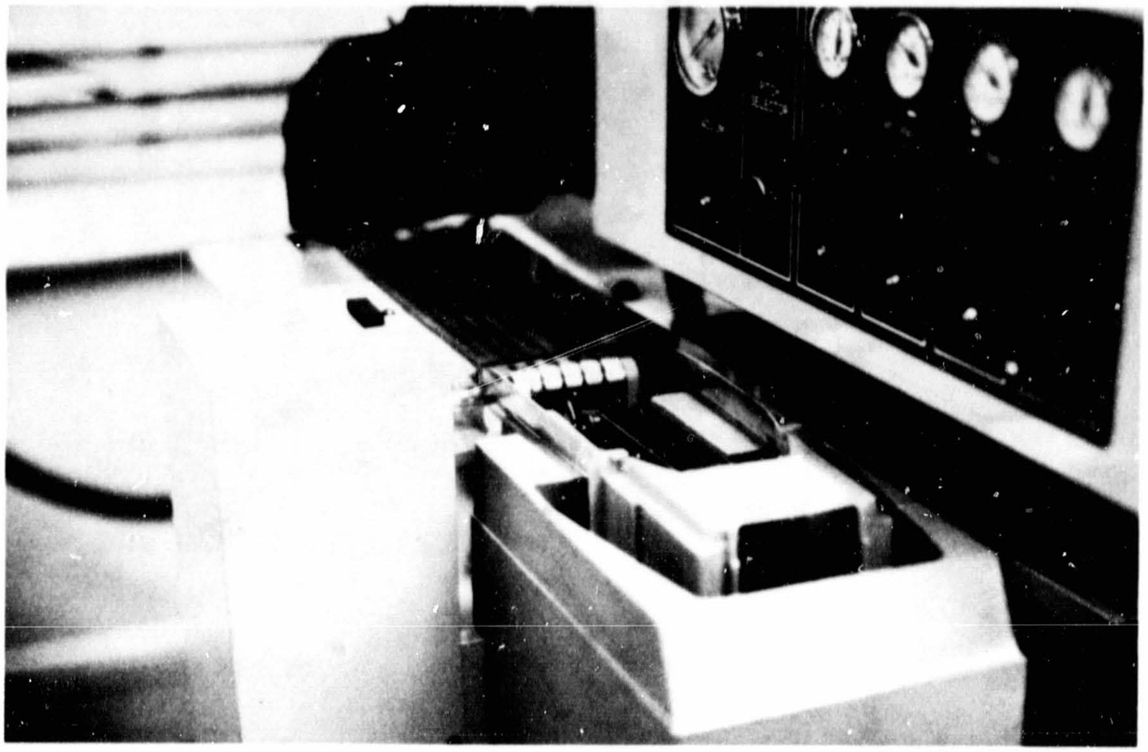
10 X 10 cm HEM Wafers With Breakage at Corners Due to Inhomogeneity



15-cm-Dia Cz Wafer Sliced With STC 32-in. ID Saw



STC Single-Slice Recovery System



MULTIWIRE SLICING: FAST

CRYSTAL SYSTEMS, INC.

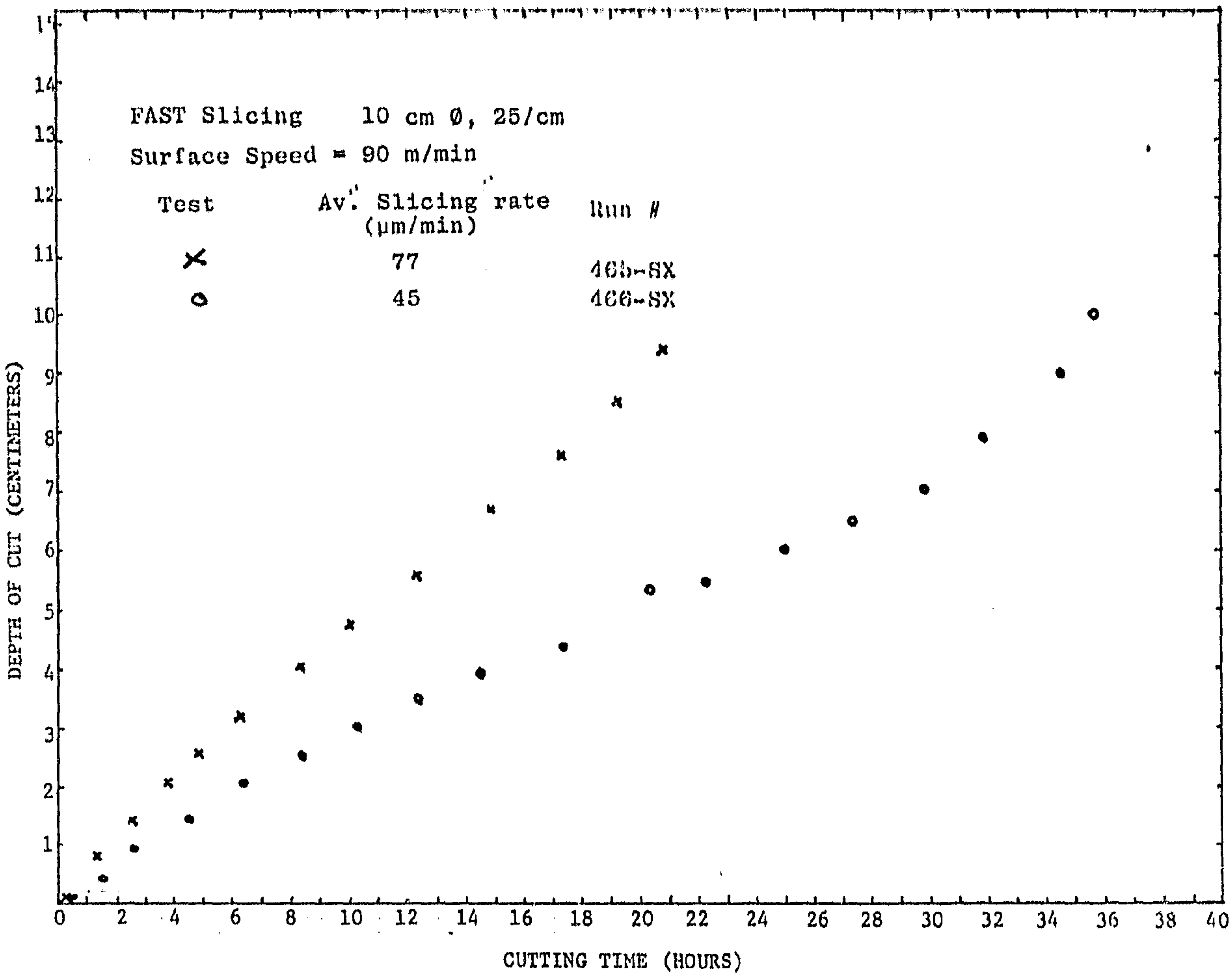
F. Schmid and C. P. Khattak

Silicon Slicing Summary

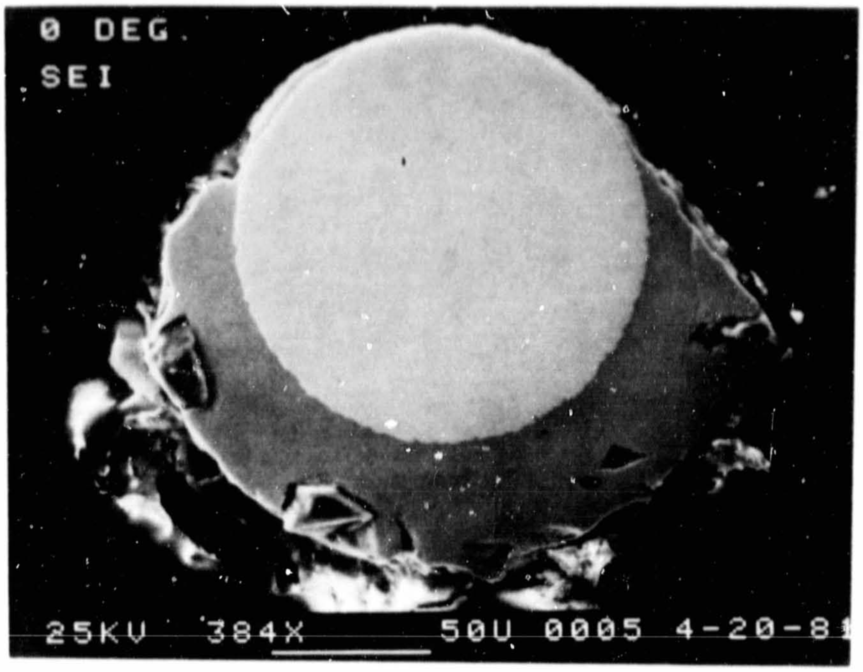
RUN	PURPOSE	FEED FORCE/BLADE lb	FEED FORCE/BLADE gm	AVERAGE CUTTING RATE mil/min	AVERAGE CUTTING RATE mm/min	WIRE TYPE	REMARKS
458-SX	Life test (2nd run)	0.084	38.1	3.6	0.091	5 mil, 0.125 mm W wire co-deposited all around with 325/400 mesh natural diamonds at CSI (same as 457-SX)	38% yield; some wires broken during slicing
459-SX	Prevent wire breakage by changing plating solution	0.084	38.0	3.1	0.079	5 mil, 0.125 mm W wire co-deposited all around with 45 μm natural diamonds at CSI	99% yield; no wire breakage
460-SX	Life test (2nd run)	0.084	38.0	2.1	0.053	Same as 459-SX	71% yield; 6.9 mils average kerf
461-SX	Test electro-formed wirepack	0.078	35.3	3.7	0.094	5 mil, 0.125 mm W wire electroformed to co-deposit 60 μm natural diamonds in a 60° V-groove	81% yield; 7.9 mils average kerf

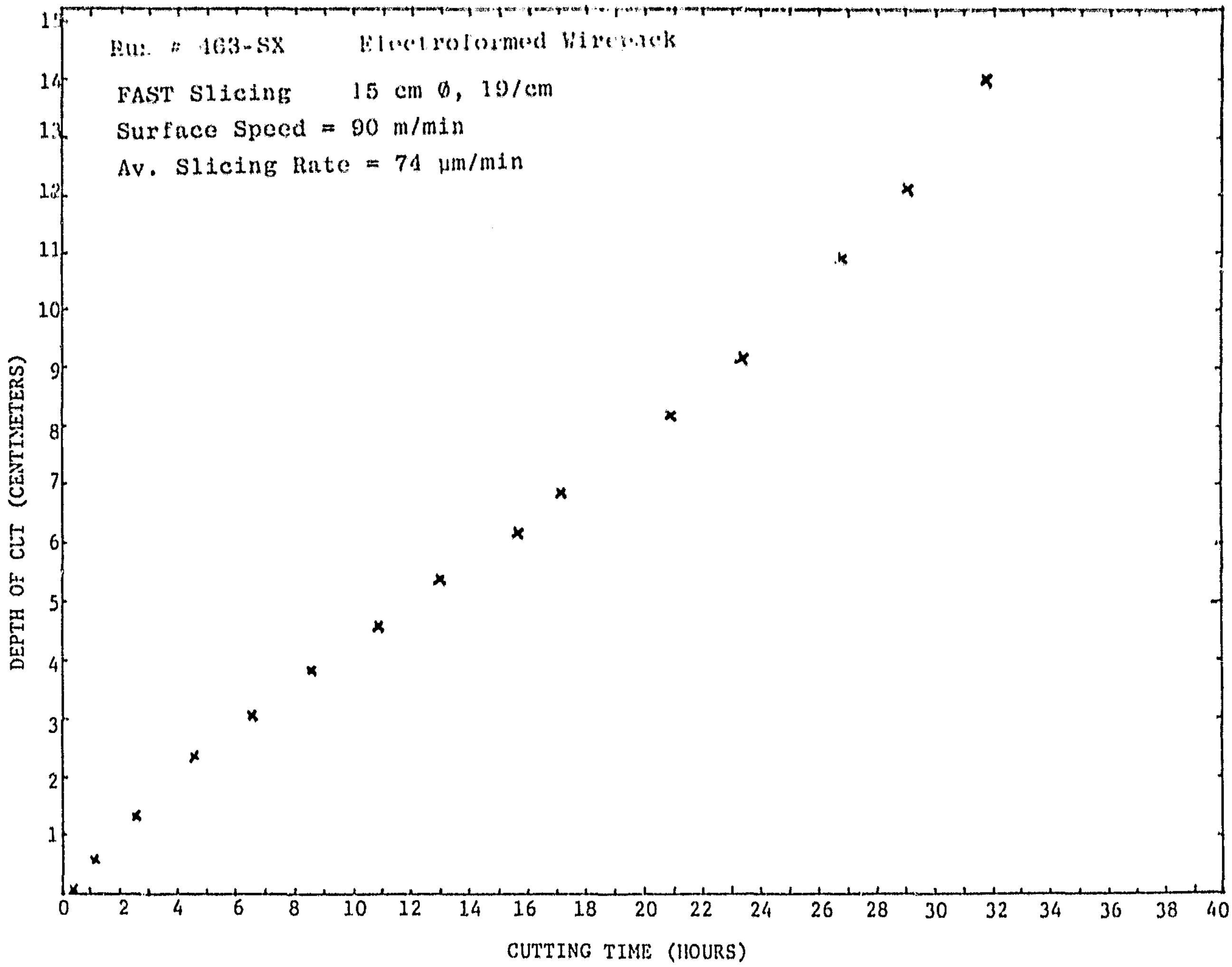
RUN	PURPOSE	FEED FORCE/BLADE lb	FEED FORCE/BLADE gm	AVERAGE CUTTING RATE mil/min	AVERAGE CUTTING RATE mm/min	WIRE TYPE	REMARKS
462-SX	Life test of electroformed wirepack (2nd run)	0.097	43.8	3.6	0.091	5 mil, 0.125 mm W wire electroformed to co-deposit 60 μm natural diamonds in a 60° V-groove at CSI (same as 461-SX)	24% yield; some wires broken because of wire wander
463-SX	Slicing of 15 cm diameter ingot with electroformed wirepack	0.084	38.0	2.9	0.074	5 mil, 0.125 mm W wire electroformed to co-deposit 60 μm natural diamonds in a 60° V-groove	20% yield; wire wander observed
464-SX	Slicing of 25 wafers/cm	0.075	34.2	3.6	0.091	5 mil, 0.125 mm W wire co-deposited with 45 μm natural diamonds	34% yield; 7.3 mils average kerf, nickel buildup was heavier on outer wires
465-SX	Slicing of 25 wafers/cm	0.053	24.2	3.0	0.076	5 mil, 0.125 mm W wire co-deposited with 30 μm natural diamonds	99.1% yield; average wafer thickness 7.7 mils
466-SX	Life test (2nd run)	0.063	28.6	1.8	0.046	Same as 465-SX	36% yield; wafer breakage in slicing the second half of ingot
467-SX	Life test (3rd run)	0.063	28.7	1.3	0.033	Same as 465-SX	Run aborted because of low cutting rates
468-SX	Slicing of 10 cm x 10 cm ingot 25 wafers/cm	–	–	–	–	5 mil, 0.125 mm W wire co-deposited with 30 μm natural diamonds	Run aborted as crystal was hitting guide rollers
469-SX	Slicing of 10 cm x 10 cm ingot 25 wafers/cm	0.054	24.4	–	–	Same as 468-SX	Run aborted due to improper tracking of wires

RUN	PURPOSE	FEED FORCE/BLADE lb	FEED FORCE/BLADE gm	AVERAGE CUTTING RATE mil/min	AVERAGE CUTTING RATE mm/min	WIRE TYPE	REMARKS
470-SX	Slice 15 cm diameter ingot	0.072	32.6	2.6	0.066	5 mil, 0.125 mm W wire electroplated with 45 μm natural diamonds all around	Wafer breakage due to entrapment of wafer fragments between wires
471-SX	Slice 10 cm diameter ingot 25 wafers/cm	0.054	24.4	2.4	0.061	5 mil, 0.125 mm W wire electroplated with 30 μm natural diamonds all around	88% yield; average wafer thickness 7.8 mils
472-SX	Slice 10 cm x 10 cm ingot 25 wafers/cm	0.054	24.4	1.3	0.033	5 mil, 0.125 mm W wire electroplated with 30 μm natural diamonds all around	46% yield
473-SX	Test suitability of steel core wire	0.072	32.6	3.5	0.089	5 mil, 0.125 mm steel core with Cu flash, electroplated with 45 μm natural diamonds. Baked at 200° F for 5 hours.	99.4% yield; no wire breakage
474-SX	Life test (2nd run)	0.072	32.8	1.7	0.043	Same as 473-SX	63% yield; no wire breakage
475-SX	Life test (3rd run)	0.075	34.0	2.6	0.066	Same as 473-SX	37% yield; diamond pull-out observed


FAST Slicing 10 cm Ø, 25/cm
Surface Speed = 90 m/min
Test
Av. Slicing rate (μm/min)
Run #
77
465-SX
45
466-SX
DEPTH OF CUT (CENTIMETERS)
CUTTING TIME (HOURS)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
1
2
3
4
5
6
7
8
9
10
11
12
13
14

Cross Section of Electroformed Wire





Choice of Core Wire

	TUNGSTEN	STEEL
YOUNG'S MODULUS	HIGH	
ELASTIC LIMIT		HIGH
CLEANING PRIOR TO PLATING	(NI FLASH)	(CU FLASH)
PLATING		EMBRITTLEMENT
COST	HIGH	

Electroplating

1. IT HAS BEEN POSSIBLE TO PREVENT BREAKAGE OF WIRE BY PLATING SOFTER NICKEL.
2. USE OF COPPER FLASH HIGH-STRENGTH STEEL AS A CORE WIRE HAS BEEN DEMONSTRATED.

Summary

1. SLICING OF 10 CM DIAMETER INGOTS AT 25 WAFERS/CM HAS BEEN DEMONSTRATED WITH OVER 99% YIELD.
2. 15 CM DIAMETER INGOTS HAVE BEEN SLICED AT 19 WAFERS/CM.
3. ELECTROFORMED WIREPACKS HAVE BEEN USED FOR EFFECTIVE SLICING.
4. SOFTER NICKEL PLATING HAS PREVENTED EMBRITTLEMENT OF WIRES.
5. CU FLASH HIGH-STRENGTH STEEL HAS BEEN DEMONSTRATED AS SUITABLE CORE MATERIAL.

Problems

1. WIRE LIFE
2. YIELDS
3. LARGE KERF LENGTH

MULTIBLADE SAWING

P. R. HOFFMAN CO.

TECHNOLOGY INGOT SLICING	REPORT DATE 7/15/81
APPROACH MULTI-BLADE SLURRY TECHNIQUE (MBS) CONTRACTOR P. R. HOFFMAN CO. (NORLIN IND.)	STATUS . 10 CM DIAMETER WORKPIECE . 1.5 MIL/MIN CUT RATE (.15 WAFER/MIN) . 18 WAFERS/CM . 95% YIELD DEMONSTRATION RECLAIM OF VEHICLE AND ABRASIVE IN LABORATORY TEST (SMALL VOLUME)
GOALS . UP TO 15 CM DIAMETER WORKPIECE . CUTTING RATE 0.5 WAFER/MINUTE . 25 WAFERS/CM . 95% YIELD . < $14.00/M^2 (1980$)	

Strategic Plan

- EVALUATE PROCESS CONSTRAINTS
- DEVELOP PROCESS IMPROVEMENTS
- EVALUATE ALTERNATIVE CONSUMABLES
- COST REDUCTION VIA RECYCLE OF VEHICLE AND ABRASIVE
- DEFINE OPTIMUM PROCESS
- EVALUATE DESIGN CONTRAINTS
- DEVELOP DESIGN IMPROVEMENTS
- DEFINE OPTIMUM SAW DESIGN CONSISTENT WITH DEFINITION OF OPTIMIZED PROCESS

Tactical Concerns: Process

- BLADE PACKAGE SPECIFICATIONS
- ABRASIVE PARTICLE SIZE
- ABRASIVE/VEHICLE RATIO
- SLURRY APPLICATION METHODS (METHODS SYSTEM)
- SLURRY APPLICATION METHODS (VOLUME)
- BLADE HEAD SPEED
- FEED FORCE/CUTTING RATE

Tactical Concerns: Cost Reduction

- EVALUATE VEHICLE RECYCLING
- EVALUATE ABRASIVE RECYCLING
- INVESTIGATE ALTERNATIVE VEHICLES
- INVESTIGATE ALTERNATIVE ABRASIVES
- INVESTIGATE ALTERNATIVE BLADE MATERIALS

Tactical Concerns: Design

- IMPROVE FEED FORCE CONTROL
- WAFER LIFT-OFF/SUPPORT DEVICE
- INGOT MOUNTING/DEMOUNTING SYSTEM
- PROCESS DEFINITION IMPACT ON EQUIPMENT DESIGN

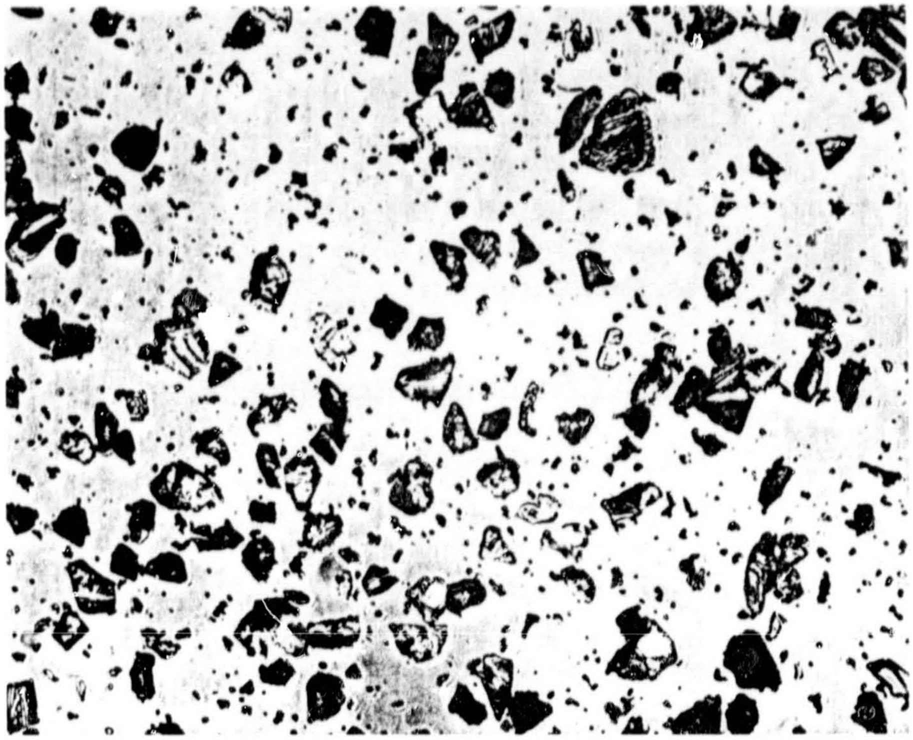
CONCERNS - INGOT MOUNTING

- ELIMINATE GRINDING OF FLAT SURFACE
- ELIMINATE EFFECTIVE "HINGE" AT BOND LINE
- BOND STRENGTH DURING WAFERING
- EASE OF RELEASE OF COMPLETED WAFERS

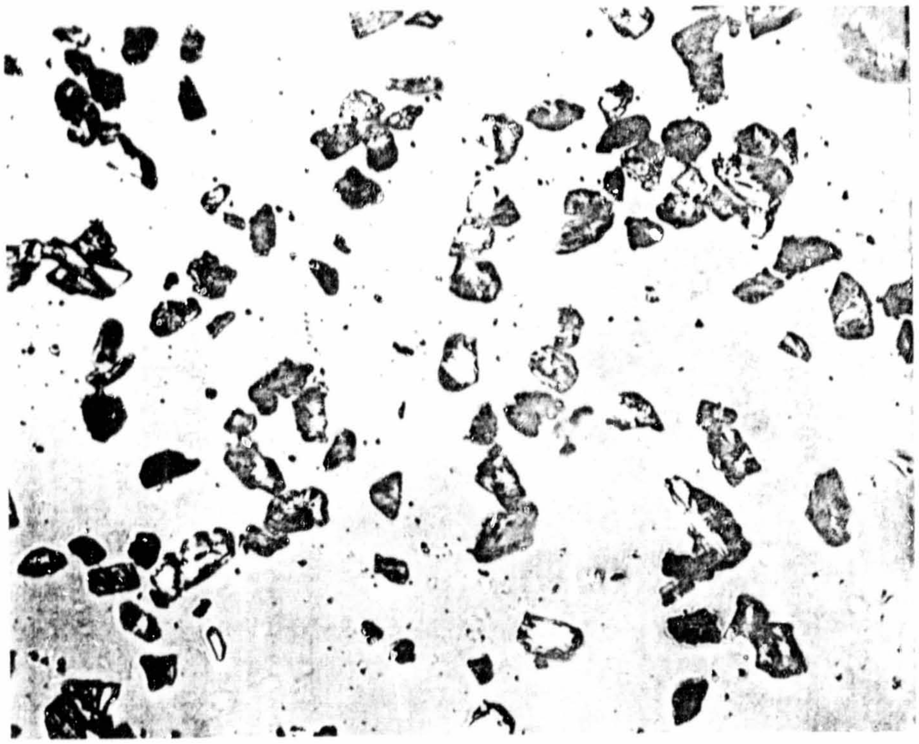
CONCERNS - WAFER LIFT-OFF DEVICE

- SUPPORT WAFERS
- AVOID STRESSES ON WAFERS
- MINIMAL OPERATOR TRAINING, ATTENTION
- COMPATIBLE WITH CLEANING PROCESS

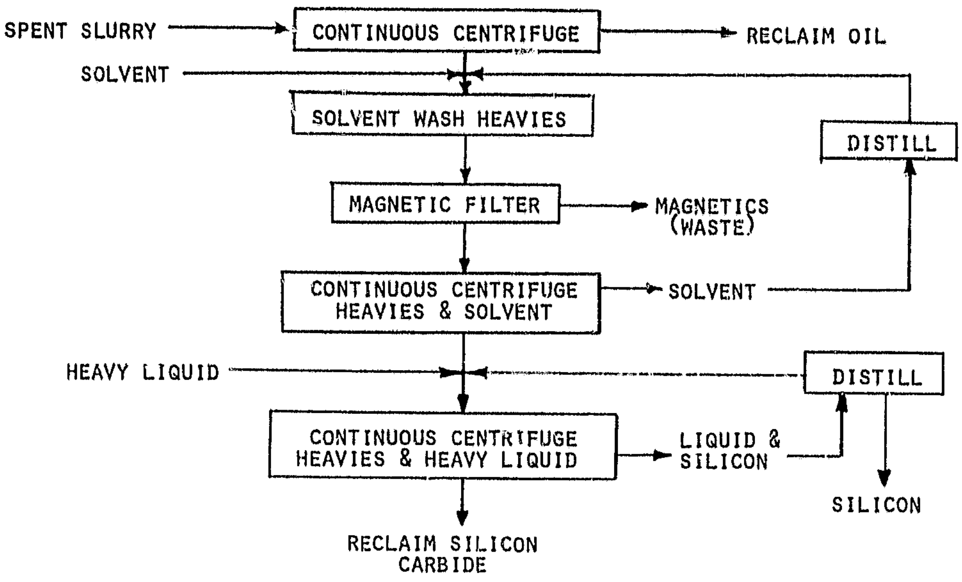
Spent Slurry, 900X



Reclaimed 600 SiC Abrasive, 900X



Reclamation of Vehicle and Abrasive: Proposed Process



Baseline Test Series Completed

- Preliminary Evaluation-effect Abrasive Particle Size (2 Tests)
- Effect Blade Head Speed on Cutting Rate (3 Tests)
- Brief Evaluation of Minimum Stroke/max Speed (Segment)
- Effect of Vertical Feed Force on Cutting Rate (4 Tests)
- Evaluate Alternative Vehicle (1 Test to date)

Cost Projections (1980 $) IPEG

ASSUMPTIONS:

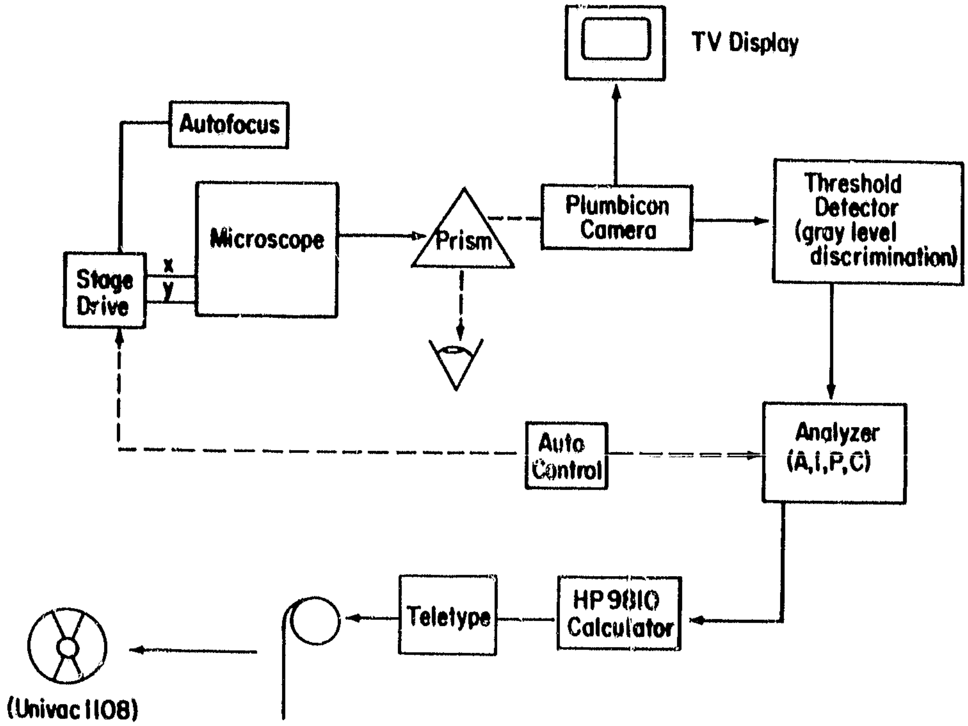
EQUIPMENT COST - $42K/MACHINE
FLOOR SPACE - 36 SQ. FT.
1 OPERATOR/15 UNITS
EXPENDABLES/RUN - $140.89 (BLADE PACK, OIL, ABRASIVE)
455 WAFERS/RUN (20 WAFERS/CM)
45 HOUR RUN TIME
95% YIELD
95% DUTY CYCLE

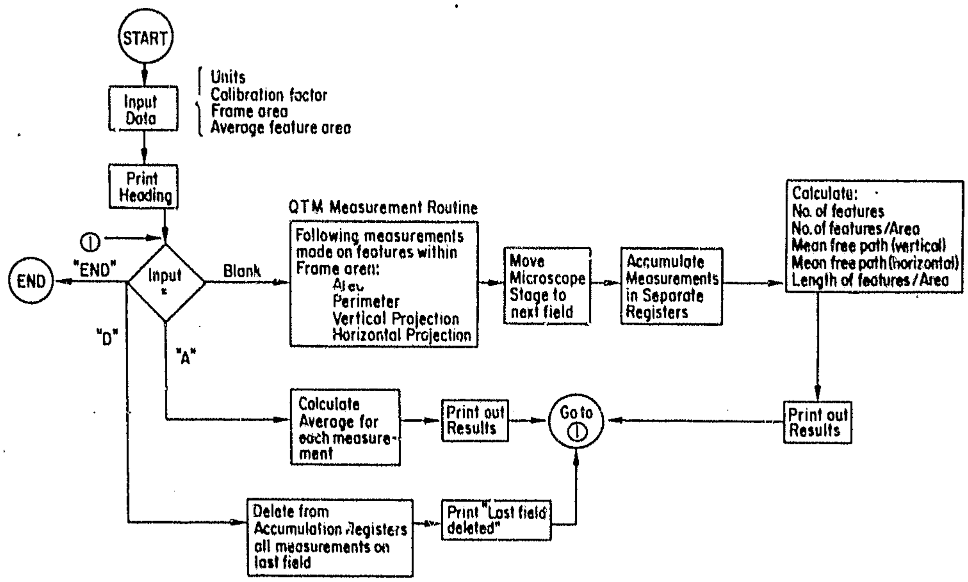
PROJECTION:
$104.4/$M^2$ VALUE ADDED

ANALYSIS OF DEFECT STRUCTURE IN SILICON

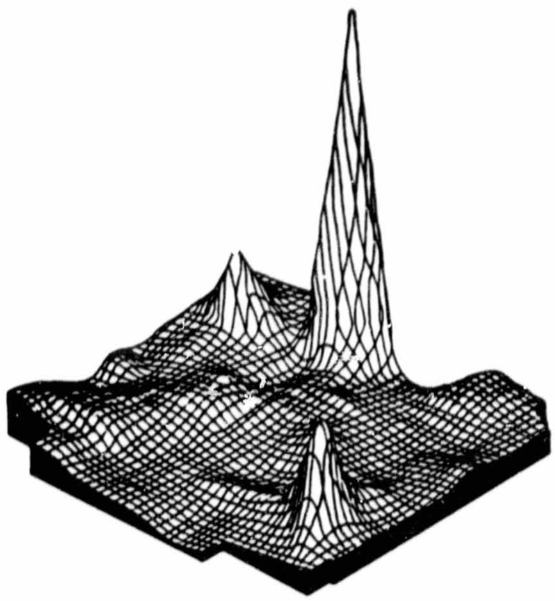
MATERIALS RESEARCH, INC.

Quantimet 720 Image Analyzer





Dislocation Density Distribution



Oblique view of a three-dimentional map showing the dislocation density distribution on the surface of a silicon wafer. The X- and the Y- axes specify the location of a point on the wafer surface, and the Z-axis gives the dislocation density at that point.

Analysis of HEM Single-Crystal ("A") Samples

Lot C-19676

Sample Number	Precipitate Density, precipitates per μm^2
A1	1.883 E-03
A2	6.095 E-03
A3	5.475 E-03
A5	4.367 E-03
A6	8.840 E-03
A7	9.910 E-03
A8	4.291 E-03
A9	8.336 E-03
A10	1.592 E-03
A11	7.585 E-03
A12	6.963 E-03
A13	6.673 E-03
A14	7.133 E-03
A15	2.541 E-03
A16	7.367 E-03
A17	1.159 E-03
A18	2.896 E-03
A19	2.387 E-03
A20	1.918 E-03
A21	3.802 E-03
A22	3.647 E-03
A23	2.589 E-03
A24	1.466 E-03
A25	1.503 E-02
Batch Average	5.149 E-03
SD	3.347 E-03

Analysis of HEM Polycrystalline ("B") Samples

Lot C-19676

Sample Number	Precipitate Density, precipitate per μm^2	Twin Density, lines per mm^2	Grain Boundary Length, mm per mm^2
B1	1.207 E-02	0.040	0.140
B2	1.088 E-02	0.011	0.314
B3	1.086 E-02	0.009	0.035
B4	8.741 E-03	0.011	0.070
B5	5.433 E-03	0.045	0.524
B6	3.717 E-03	0.045	0.524
B7	2.867 E-03	0.107	0.489
B8	1.697 E-03	0.027	0.175
B9	1.827 E-03	0	0
B10	2.170 E-03	0.174	0.838
B11	2.510 E-03	0.011	0.593
B12	2.024 E-03	0.113	0.454
B13	3.326 E-03	0.040	0.244
B14	1.987 E-03	0.071	0.244
B16	2.205 E-03	0.153	0.244
B17	3.275 E-03	0.017	0.035
B18	2.008 E-03	0.018	0.454
B19	2.575 E-03	0.061	0.279
B20	2.441 E-03	0.085	0.279
Batch Average	4.384 E-03	0.055	0.312
SD	3.490 E-03	0.051	0.222

Summary of Results for 72 HEM Samples

Sample Number	Dislocation Pit Density, pits per mm^2	Precipitate Density, precipitate per μm^2	Twin Density, lines per mm^2	Grain Boundary Length, mm per mm^2
1A2-1	1.667	1.990 E-03	0	0.022
1A2-2	1.951	1.954 E-03	0	0
1A2-3	3.333	3.102 E-03	3.059	0
2A2-5	1.442	2.058 E-03	1.413	0.201
2A2-6	1.456	2.480 E-03	39.716	0.254
1B4-1	2.691	5.194 E-03	15.425	0.117
1B4-2	1.844	2.615 E-03	0	0
1B4-L	0.997	2.417 E-03	0	0.052
2B4-1	0.699	3.700 E-03	2.454	0.419
2B4-2	3.320	5.173 E-03	4.153	0.638
2B4-3	5.590	3.157 E-03	16.848	0.445
3B4-1	1.404	1.670 E-03	0	0.055
3B4-2	1.185	2.919 E-04	0	0
4B10-1	1.361	1.329 E-03	8.105	0.150
4B10-2	1.014	1.162 E-02	9.315	0.273
4B10-3	0.787	6.078 E-03	22.735	0.144
7B8-1	4.000	3.231 E-03	16.286	0.489
7B8-2	6.444	2.113 E-03	27.378	0.524
7B8-3	2.667	1.417 E-03	23.449	0.419
7B8-5	2.000	9.775 E-04	38.777	0.349
7B8-6	4.222	1.892 E-03	68.868	0.489
7B8-7	10.222	1.914 E-03	0	0.070
7B8-9	4.889	1.657 E-03	13.752	0.454
7B8-10	2.167	4.185 E-03	1.539	0.131
7B8-11	5.882	9.044 E-04	7.989	0.334

Sample Number	Dislocation Pit Density, pits per mm^2	Precipitate Density, precipitate per μm^2	Twin Density, lines per mm^2	Grain Boundary Length mm per mm^2
7B8-13	2.220	1.268 E-03	16.357	0.175
7B8-14	2.764	1.676 E-03	5.471	0.230
7B8-15	1.667	1.103 E-03	4.024	0.183
1C4-1	0.699	1.068 E-02	7.497	0.100
1C4-2	1.570	3.132 E-03	24.226	0.648
1C4-3	2.100	2.596 E-03	17.969	0.449
2C4-1	6.110	2.831 E-03	2.430	0.937
2C4-2	9.260	4.958 E-04	4.575	0.541
2C4-3	0.349	1.683 E-03	8.266	0.604
3C8-1	4.651	1.486 E-03	1.887	0.268
3C8-2	4.167	3.111 E-03	23.491	0.491
3C8-3	2.667	1.094 E-03	19.943	0.524
3C8-5	2.862	1.612 E-03	4.315	0.476
3C8-6	2.299	3.020 E-03	20.610	0.645
4C4-1	0.524	1.398 E-03	12.778	0.209
4C4-2	1.050	2.099 E-03	6.783	0.105
4C4-3	0.349	6.616 E-04	7.957	0.279
7M2-2	8.673	6.368 E-03	1.017	0.267
7M2-3	3.876	9.221 E-03	1.987	0.950
7M2-4	3.182	1.504 E-03	24.352	0.571
7M2-6	3.684	4.726 E-03	0	0.110
7M2-7	3.158	3.096 E-03	3.463	0.165
7M2-8	2.444	1.282 E-02	10.866	0.559
7M2-10	2.889	7.483 E-03	3.547	0.349
7M2-11	2.889	5.546 E-03	0	0.035

Sample Number	Dislocation Pit Density, pits per mm^2	Precipitate Density, precipitate per μm^2	Twin Density, lines per mm^2	Grain Boundary Length, mm per mm^2
7M2-12	8.889	3.373 E-03	6.117	0.454
7M2-14	25.556	8.467 E-03	19.441	0.803
7M2-15	4.444	6.644 E-03	12.595	0.384
7M2-16	3.556	3.281 E-03	0	0.244
7M2-19	11.000	3.407 E-03	17.745	0.244
7T7-1	4.127	3.299 E-03	7.976	0.150
7T7-2	6.667	2.434 E-03	11.208	0.224
7T7-3	3.167	4.571 E-03	31.734	0.340
7T7-4	2.857	8.647 E-03	24.571	0.324
7T7-5	3.167	4.389 E-03	50.215	0.419
7T7-6	1.789	4.608 E-03	124.943	0.230
7T7-7	1.754	3.854 E-03	23.412	0.138
7T7-8	5.200	7.654 E-03	25.003	0.128
7T7-9	3.758	3.507 E-03	49.668	0.282
7T7-10	3.454	4.818 E-03	28.845	0.217
7T7-11	4.615	1.804 E-03	46.132	0.242
7T7-12	3.810	2.307 E-03	88.872	0.474
9A7-1	2.763	7.390 E-03	1.884	0.145
9A7-2	0.524	1.805 E-03	1.355	0.105
9A7-3	15.700	3.060 E-03	39.560	0.663
9A7-4	4.540	1.379 E-03	6.869	0.419
9A7-5	1.750	6.101 E-03	10.195	0.079

Group Averages for 72 HEM Samples

Sample Number	Dislocation Pit Density, pits per mm^2	Precipitate Density, precipitate per μm^2	Twin Density, lines per mm^2	Grain Boundary Length, mm per mm^2
1A2	2.317	2.349 E-03	1.170	0.007
2A.	1.449	2.269 E-03	20.565	0.228
1B4	1.844	3.409 E-03	5.142	0.056
2B4	3.203	4.010 E-03	7.818	0.567
3B4	1.295	9.810 E-04	0	0.028
4B10	1.054	2.856 E-03	13.385	0.189
7B8	3.929	1.861 E-03	18.658	0.321
1C4	1.456	5.469 E-03	16.564	0.399
2C4	5.240	1.670 E-03	5.090	0.694
3C8	3.329	2.065 E-03	14.049	0.466
4C4	0.641	1.386 E-03	9.053	0.198
7M2	6.480	5.841 E-03	7.779	0.392
7T7	3.697	4.324 E-03	42.714	0.264
9A7	5.037	4.047 E-03	11.973	0.282

Analysis of Mobil Tyco EFG Samples

Sample Number	Dislocation Pit Density, per μm^2	Twin Density, per mm^2	Grain Boundary Length, mm/mm^2
EFG 17-139-A	1.545 E-02	453.553	0.568
(CO_2 OFF) B	1.264 E-02	403.335	0.171
C	7.337 E-03	1192.780	0.114
D	2.490 E-02	179.962	0.229
E	4.632 E-03	695.013	-
EFG 17-139-F	2.070 E-02	144.057	0.514
(CO_2 ON) G	3.292 E-02	204.798	0.600
H	9.712 E-03	322.519	0.379
I	7.616 E-03	96.891	0.400
J	1.597 E-02	295.899	0.947
EFG 17-143-A	3.022 E-02	499.521	0.189
(CO_2 OFF) B	1.415 E-02	611.570	1.326
C	2.219 E-02	289.859	0.253
D	1.346 E-02	228.574	0.286
E	1.530 E-02	368.724	0.540
EFG 17-143-F	8.796 E-03	473.206	0.180
(CO_2 ON) G	8.673 E-03	763.656	0.267
H	1.773 E-02	349.726	0.293
I	1.887 E-02	331.244	0.706
J	2.379 E-02	354.361	1.123
EFG 17-146-A	2.824 E-02	229.454	0.960
B	3.130 E-02	460.619	0.253
C	3.503 E-02	165.054	0.424
D	1.253 E-02	381.455	0.112
E	2.283 E-02	218.708	0.884

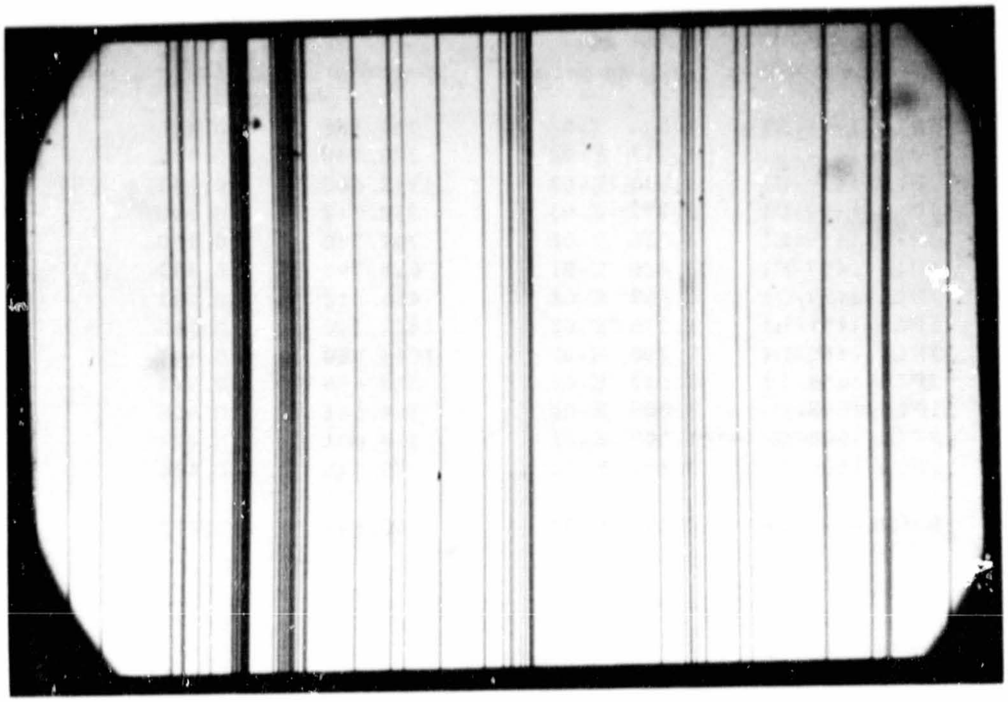
Batch Averages of Mobil Tyco Sample Measurements

Batch Number	Dislocation Pit Density, per μm^2	Twin Density, per mm^2	Grain Boundary Length, mm/mm^2
EFG 17-139 (CO_2 OFF)			
a) Average	1.299 E-02	584.929	0.271
b) SD	7.903 E-03	385.952	0.284
EFG 17-139 (CO_2 ON)			
a) Average	1.738 E-02	212.833	0.568
b) SD	1.011 E-02	96.325	0.230
EFG 17-143 (CO_2 OFF)			
a) Average	1.906 E-02	399.650	0.519
b) SD	7.141 E-03	155.854	0.471
EFG 17-143 (CO_2 ON)			
a) Average	1.557 E-02	454.441	0.514
b) SD	6.644 E-03	181.749	0.392
EFG 17-146			
a) Average	2.599 E-02	291.058	0.527
b) SD	8.748 E-03	124.327	0.378
EFG 17-139 (combined)			
a) Average	1.519 E-02	398.881	0.436
b) SD	8.861 E-03	329.839	0.258
EFG 17-143 (combined)			
a) Average	1.732 E-02	427.045	0.516
b) SD	6.758 E-03	162.206	0.410

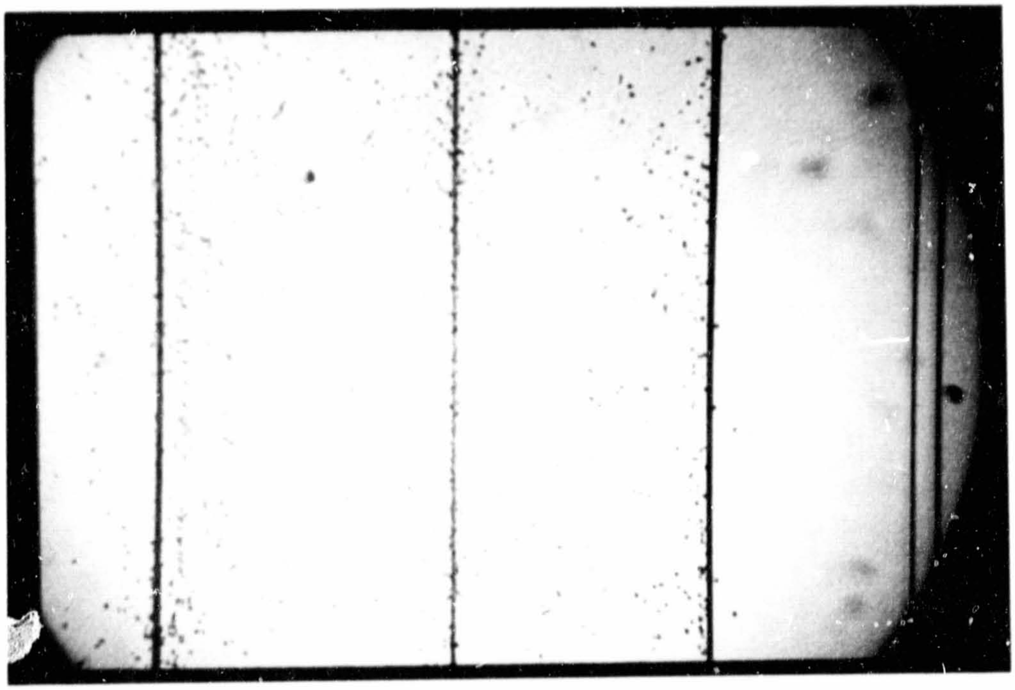
Mobil Tyco EFG Sample Measurement Summary

Sample Number	Dislocation Pit Density per μm^2	Twin Density per mm^2	Grain Boundary Length, mm/mm^2
JPL5-1459-A1	1.834 E-02	741.888	0.182
JPL5-1459-B1	3.412 E-02	306.540	0.136
JPL5-1459-C1	1.951 E-02	1142.460	0.143
JPL5-1459-D1	8.777 E-03	750.317	0.190
JPL5-1459-E1	1.026 E-02	747.730	0.150
JPL5-1459-F1	2.226 E-02	638.795	0.182
JPL5-1459-G1	2.692 E-02	464.212	0.087
JPL5-1459-H1	1.275 E-02	1441.190	0.045
JPL5-1459-I 1	7.798 E-02	1044.880	0.143
JPL5-1459-J 1	2.617 E-02	850.496	0.571
JPL5-1508-F	2.005 E-02	864.541	0.905
JPL5-1508-G	1.609 E-02	558.001	0.409
JPL5-1508-J	3.865 E-02	79.940	0.400
Batch Average	2.553 E-02	740.845	0.273

EFG Material, 200X



EFG Material, 400X



Analysis of Honeywell Samples V-00578

Grain Boundary Length

Sample #	Number of Fields taken	Average Grain Boundary Length (mm/mm^2)	Standard Deviation	Relative Error at 90% Confidence (%)
B2	0[a]	——	——	——
B3	18[b]	16.7611	5.8463	14.31
B4	31	9.0151	4.9943	16.37
D2	5[b]	15.8789	3.8895	23.35
D3	12[b]	15.0850	2.7503	9.45
D4	32	13.5962	7.4908	16.02
H1L	10[b]	10.4801	3.6823	20.37
H1R	10[b]	13.9735	2.6781	11.11
H2L	32	6.5501	3.6910	16.39
H2R	32	6.4508	3.8250	17.24
H5L	32	7.9395	2.9084	10.65
H5R	32	9.4281	4.4537	13.74
T1L	32[b]	19.1540	6.2214	9.45
T1R	32[b]	17.2634	4.7680	8.03
T2L	32	13.3979	4.6152	10.02
T2R	32	10.7183	4.4731	12.14
T5L	32	9.3239	5.0335	15.69
T5R	32	13.1994	5.5366	12.20
M	32	4.9622	3.9466	23.13

a) All the Si has been etched out

b) Plenty of uncovered areas

Twin Density

Sample #	Number of Fields taken	Average Twin Density (per mm^2)	Standard Deviation	Relative Error at 90% Confidence (%)
B2	0[a]	———	———	———
B3	18[b]	909.5106	202.3057	9.12
B4	31	624.6091	319.2008	15.10
D2	5[b]	897.3880	166.5779	17.70
D3	12[b]	978.7627	236.6235	12.53
D4	32	822.3684	317.5137	11.23
HIL	10[b]	808.8643	427.8349	30.66
HIR	10[b]	1072.0222	267.3229	14.45
H2L	32	568.7327	430.6487	22.02
H2R	32	801.0285	373.5975	13.56
H5L	32	533.2410	192.1538	10.48
H5R	32	624.1343	244.1130	10.86
TIL	32[b]	625.0000	304.8766	14.19
TIR	32[b]	1034.4529	269.6022	7.58
T2L	32	892.4861	432.0150	14.08
T2R	32	654.4321	306.0798	13.60
T5L	32	719.3550	315.9518	12.77
T5R	32	909.7992	430.8287	13.77
M	32	534.1066	336.8394	18.32

a- All the Si has been etched out

b- Plenty of uncovered areas

C-3

Dislocation Density

Sample #	Number of Fields taken	Average Dislocation Density (Pits/μm^2)
B2	0[b]	———
B3	10	1.5013 E-2
B4	25	2.1918 E-2
D2	3[a]	8.7300 E-3
D3	5[a]	1.328 E-2
D4	25	1.2532 E-2
HIL	5[a]	7.0180 E-2
HIR	5	7.1800 E-3
H2L	25	9.4530 E-3
H2R	25	1.7050 E-2
H5L	25	5.9459 E-3
H5R	36	9.2352 E-3
TIL	10	1.2229 E-2
TIR	10	2.4692 E-2
T2L	26	7.6482 E-3
T2R	36	7.6761 E-3
T5L	25	7.8268 E-3
T5R	25	1.0575 E-2
M	16	6.0893 E-3
B5E	4[a]	3.8191 E-2
B1E	3[a]	2.4200 E-2
D5E	4[a]	3.4410 E-2
ME	4[a]	5.2938 E-2

a- Measured Manually

b- No Si on surface

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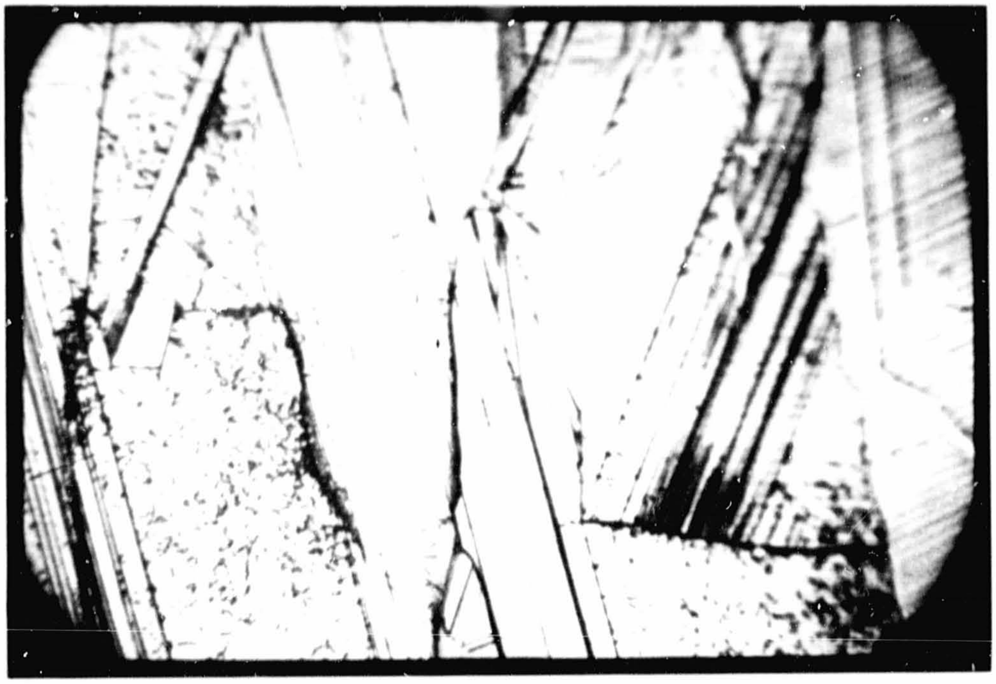
SOC Material, 400X



Analysis of Westinghouse Samples

JPL Sample #	No. of Dislocations Pits/field	No. of Dislocations Pits/μm^2
J250-4.7-A	17.808	2.737×10^{-4}
J250-4.7-B	14.946	2.298×10^{-4}
J250-4.7-C	12.146	1.867×10^{-4}
J250-4.7-D	16.614	2.554×10^{-4}
J250-4.7-E	15.526	2.387×10^{-4}
J250-4.7-F	15.800	2.429×10^{-4}
J250-4.7-K_1	15.828	2.433×10^{-4}
J250-4.7-K_2	16.615	2.554×10^{-4}
J250-4.7-L_1	37.424	5.753×10^{-4}
J250-4.7-L_2	27.082	3.702×10^{-4}

Summary of Analysis of Solar Cell Samples

EFG–3

Etch Number	Surface Analyzed	Distance from Original Surface, mils	Dislocation Pit Density, pits per μm^2	Twin Density, lines per mm^2	Grain Boundary Length, mm per mm^2
1	Top	0	-	71.982	0.240
2	Top	0.75	1.315 E-02	317.080	0.240
	Bottom	0.75	9.114 E-02	168.144	0.240
3	Top	1.55	3.224 E-02	72.632	0.240
	Bottom	1.55	3.930 E-02	40.027	0.240

EFG–13

Etch Number	Surface Analyzed	Distance from Original Surface, mils	Dislocation Pit Density, pits per μm^2	Twin Density, lines per mm^2	Grain Boundary Length, mm per mm^2
1	Top	0	-	322.892	0.060
2	Top	0.75	1.888 E-02	636.844	0.060
	Bottom	0.75	4.450 E-02	542.678	0.060
3	Top	2.45	3.414 E-02	1172.860	0.060
	Bottom	2.45	2.746 E-02	475.622	0.060

EFG–31

Etch Number	Surface Analyzed	Distance from Original Surface, mils	Dislocation Pit Density, pits per μm^2	Twin Density, lines per mm^2	Grain Boundary Length, mm per mm^2
1	Top	0	-	567.258	1.020
2	Top	0.40	1.974 E-02	459.326	1.020
	Bottom	0.40	3.247 E-02	319.204	1.020

EFG–33

Etch Number	Surface Analyzed	Distance from Original Surface, mils	Dislocation Pit Density, pits per μm^2	Twin Density, lines per mm^2	Grain Boundary Length, mm per mm^2
1	Top	0	-	207.833	0.180
2	Top	1.25	2.227 E-02	386.874	0.180
	Bottom	1.25	4.324 E-02	190.946	0.180
3	Top	2.50	2.012 E-02	382.469	0.180
	Bottom	2.50	1.425 E-02	339.582	0.180

Analysis of Variance for Solar Cells (Dislocation Pits)

EFG–3

Source of Variation	Sum of Squares	Degrees Of Freedom	Mean Square	$F_{computed}$	F_{test}, $\alpha = .05$
Different Surface Planes	9.996 E-02	3	3.332 E-02	23.20	2.68
Difference Within a Plane	1.665 E-01	116	1.436 E-03		
Total	2.665 E-01	119			

Conclusion: The average dislocation pit density for solar cell EFG-3 varies from plane to plane.

EFG–13

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	$F_{computed}$	F_{test} $\alpha = .05$
Different Surface Planes	1.055 E-02	3	3.517 E-03	2.86	2.68
Difference Within a Plane	1.429 E-01	116	1.232 E-03		
Total	1.535 E-01	119			

Conclusion: The average dislocation pit density for solar cell EFG-13 varies from plane to plane.

EFG–33

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	$F_{computed}$	F_{test} $\alpha = .05$
Different Surface Planes	1.437 E-02	3	4.790 E-03	5.58	2.68
Difference Within a Plane	9.963 E-02	116	8.589 E-04		
Total	1.140 E-01	119			

Conclusion: The average dislocation pit density for solar cell EFG-33 varies from plane to plane.

Hamco 101–1

Etch Number	Surface Analyzed	Distance from Original Surface, mils	Precipitate Density precipitate per μm^2	Twin Density, lines per mm^2	Grain Boundary Length, mm per mm^2
1	Top	0	0	0	0
2	Top	1.10	0	0	0
	Bottom	1.10	0	0	0
3	Top	3.10	3.076 E-04	0	0
	Bottom	3.10	5.006 E-04	0	0

Hamco 101–4

Etch Number	Surface Analyzed	Distance from Original Surface, mils	Precipitate Density, precipitate per μm^2	Twin Density, lines per mm^2	Grain Boundary Length, mm per mm^2
1	Top	0	0	10.145	0
2	Top	0.90	0	0	0
	Bottom	0.90	0	0	0
3	Top	1.80	3.438 E-03	0	0
	Bottom	1.80	3.965 E-03	0	0

Hamco 108–1

Etch Number	Surface Analyzed	Distance from Original Surface, mils	Precipitate Density, precipitate per μm^2	Twin Density, lines per mm^2	Grain Boundary Length, mm per mm^2
1	Top	0	0	0	0
2	Top	0.80	0	0	0
	Bottom	0.80	0	0	0
3	Top	1.55	3.042 E-03	0	0
	Bottom	1.55	5.375 E-03	0	0

Analysis of Defects in Silicon: Summary

Coupon Type	Number of Coupons	Dislocation Pit Density, Pits per μm^2	Precipitate Density Precipitates per μm^2	Twin Density Lines per mm^2	Grain Boundary Length mm per mm^2	Conversion Efficiency, %
HEM:						
a) Single crystal	24	0	5.149×10^{-3}	0	0	
b) Poly crystal						
i) Batch 1	19	0	4.384×10^{-3}	0.055	0.312	
ii) Batch 2	72	3.752×10^{-6}	3.482×10^{-3}	15.437	0.315	
EFG:						
a) CO_2 on	10	1.648×10^{-2}	0	333.637	0.541	
b) CO_2 off	10	1.603×10^{-2}	0	492.290	0.395	
c) Unclassified	18	2.566×10^{-2}	0	615.904	0.344	
Silicon-on Ceramics	23	1.864×10^{-2}	0	778.350	11.844	
Dendritic Web	10	2.871×10^{-4}	0	0	0	10.68

ADVANCED DENDRITIC WEB GROWTH DEVELOPMENT

WESTINGHOUSE ELECTRIC CORP.

Technology Single crystal ribbon growth	Report Date 07/15/81
Approach Silicon dendritic web growth **Contractor** Westinghouse Electric Corp. Research & Development Center JPL Contract 955843 **Goals** • Automated melt-replenished growth period to 65 hours • Area rate of growth 25 cm^2/min • Length of web crystal >10 meters • Dislocation density $<10^4/cm^2$ • Resistivity 1 to 3 ohm-cm p-type • Terrestrial solar cell efficiency >15% • Demonstrate advanced throughput to 30-35 cm^2/min area growth rate	**Status** • Advanced throughput development in progress, computer models developed and verified • Design of prototype web growth machine complete, new concepts verified • Fabrication and assembly of prototype web growth machine underway, on schedule

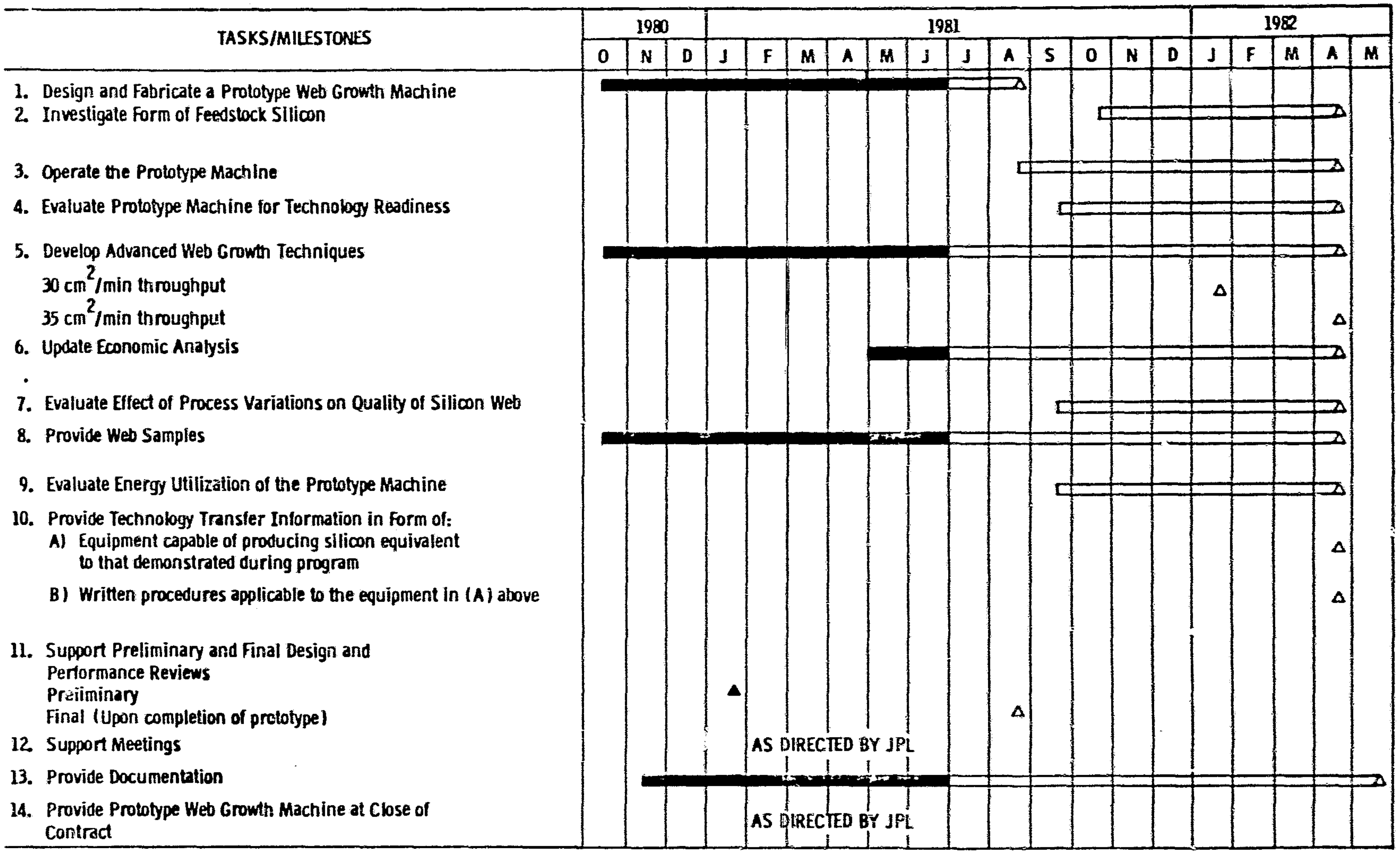
1986 Cost Projection per SAMICS/IPEG (1980 $)

Assumptions:

Area throughput rate 25 cm^2/minute
Terrestrial Cell efficiency 15%
Continuously melt-replenished 3 day growth cycle
Automated growth
Solar grade polysilicon price $14/kg
Thickness 150 μm

	Projected Cost, $/$W_{pk}$
Value-Added Sheet Cost	.151
Polysilicon Cost	.039
Total Sheet Cost	.190
DOE/JPL 1986 Goal	.224

Milestone Chart



Work in Progress

- **Development of advanced web growth techniques for high throughput**
- **Fabrication and assembly of prototype web growth machine**

Development Plan

Advanced Web Growth Techniques For High Throughput

High Speed Growth Increase dissipation of latent heat.

- Develop new lid design
- Develop new shield configurations
- Control melt height (continuous melt replenishment)
- Manage gas flow

Wide Web Growth Manage melt profile and thermal stress

- Control thermal stress (elastic)
  - Develop criteria for buckling stress
  - Identify acceptable thermal profile in web
  - Design lid/shield system to generate this profile
- Maintain control of melt profile

Combine Speed and Width Designs

Status

Advanced Web Growth Techniques For High Throughput

High Speed Growth

- A lid and shield design concept for improved speed with stable growth conditions has been demonstrated
- Automatically controlled melt level is now established
- Methods for control of gas flow and oxide deposition have been developed

Wide Web Growth

- Melt profile control is now routinely attained
- A computer model for critical buckling stress has been developed and verified
- A computer model of thermal stress/temperature profile is developed and in use

Status of Design of Prototype Web Growth Machine

Mechanical Design

- Detail design drawings complete
- Assembly drawings nearing completion

Electronic Design

- Design complete
- Detail design drawings nearing completion

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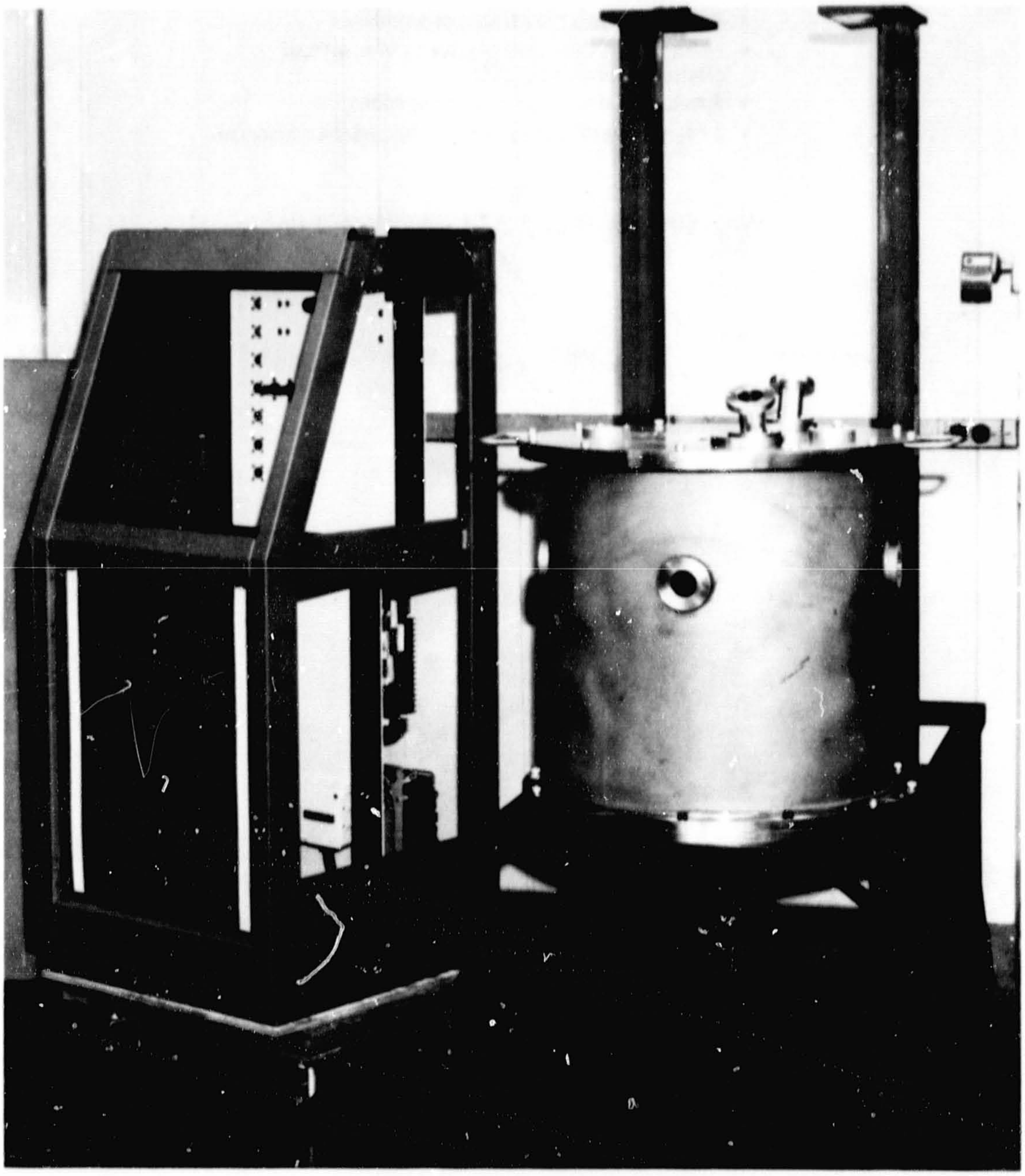
Prototype Furnace and Controller: Initial State of Assembly

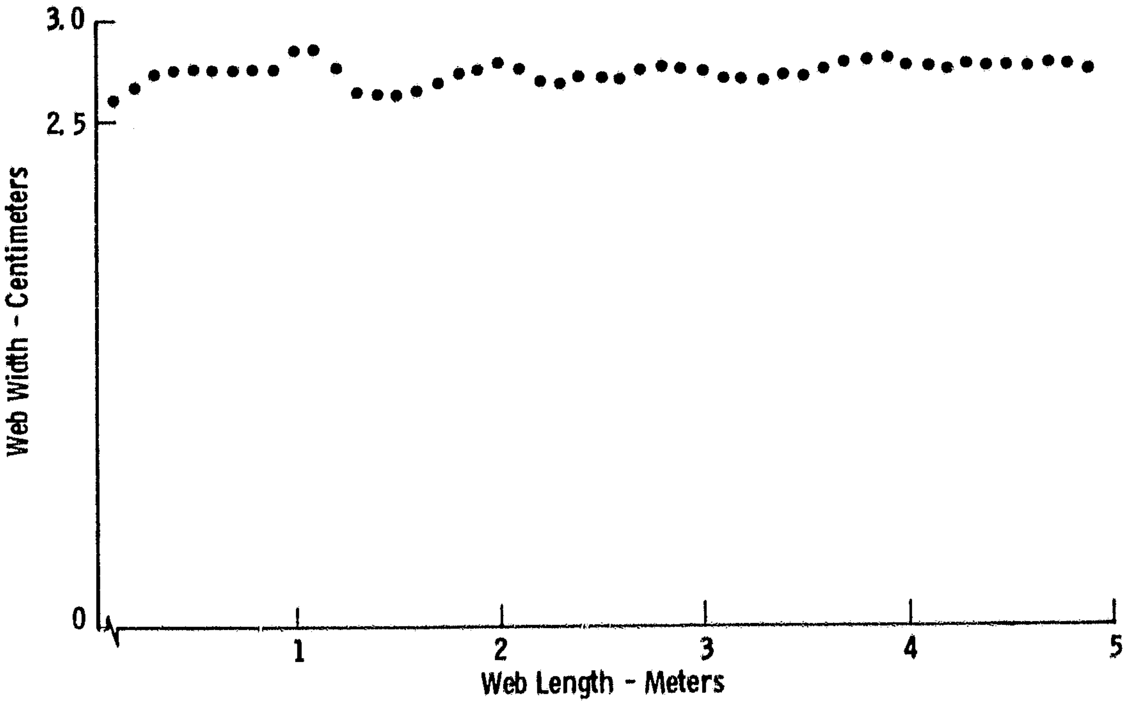


Automatic Web Width Control

Now Functional:

- Holds width to within tenths of millimeter
- Low-cost principle uses passive shields without electronics or moving parts
- Simple operation requires little operator skill
- 3 cm web width routine, 5 cm width under development

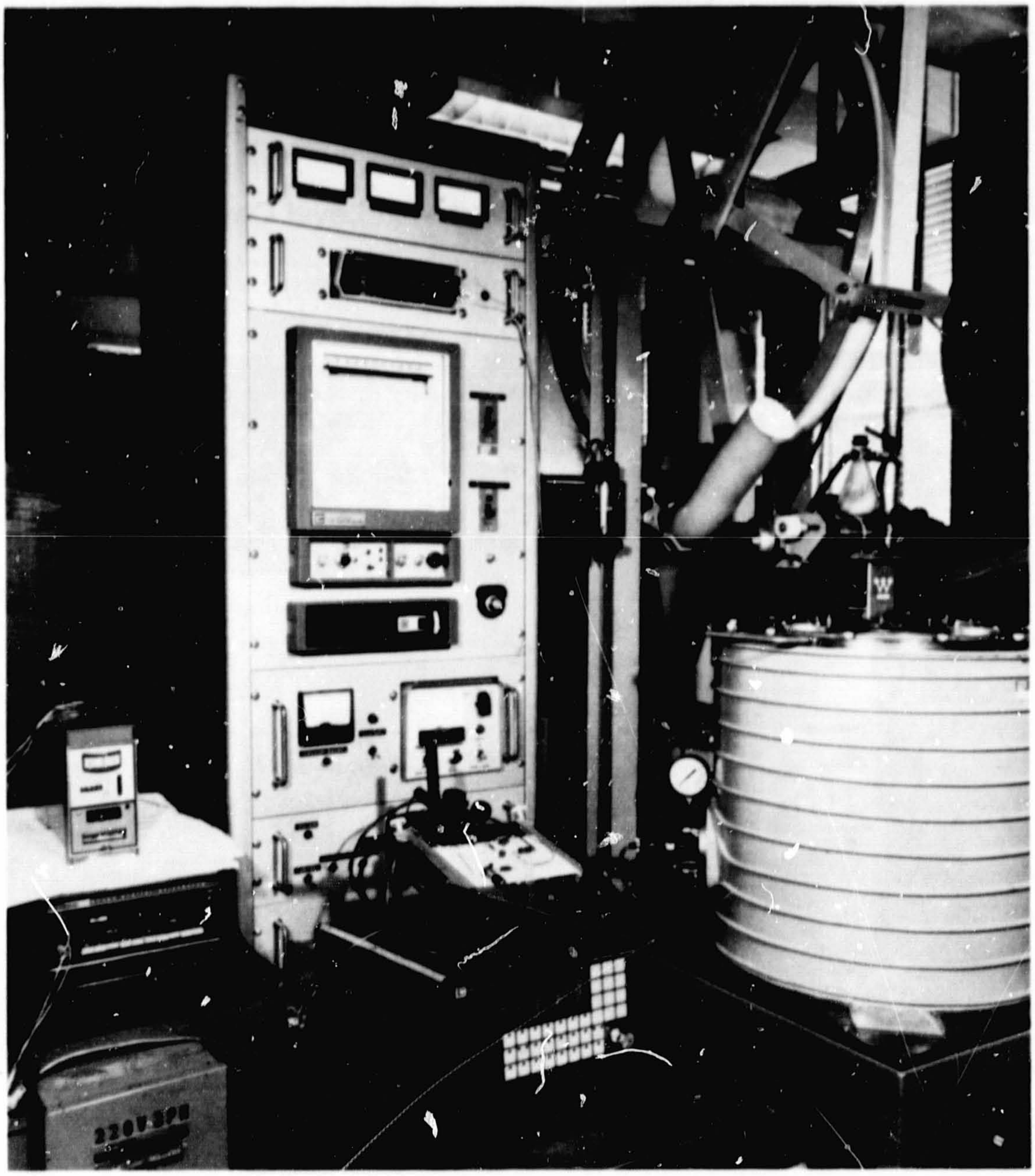
Web Growth Run J-374, Width vs Length



Programmed Start of Growth

- Repeatable high quality wide starts demonstrated
- Standard commercial process programmer is used
- Minimal operator skill required
- Single programmer serves many furnaces

Test Setup for Programmed Start
(Programmer at Front Center)



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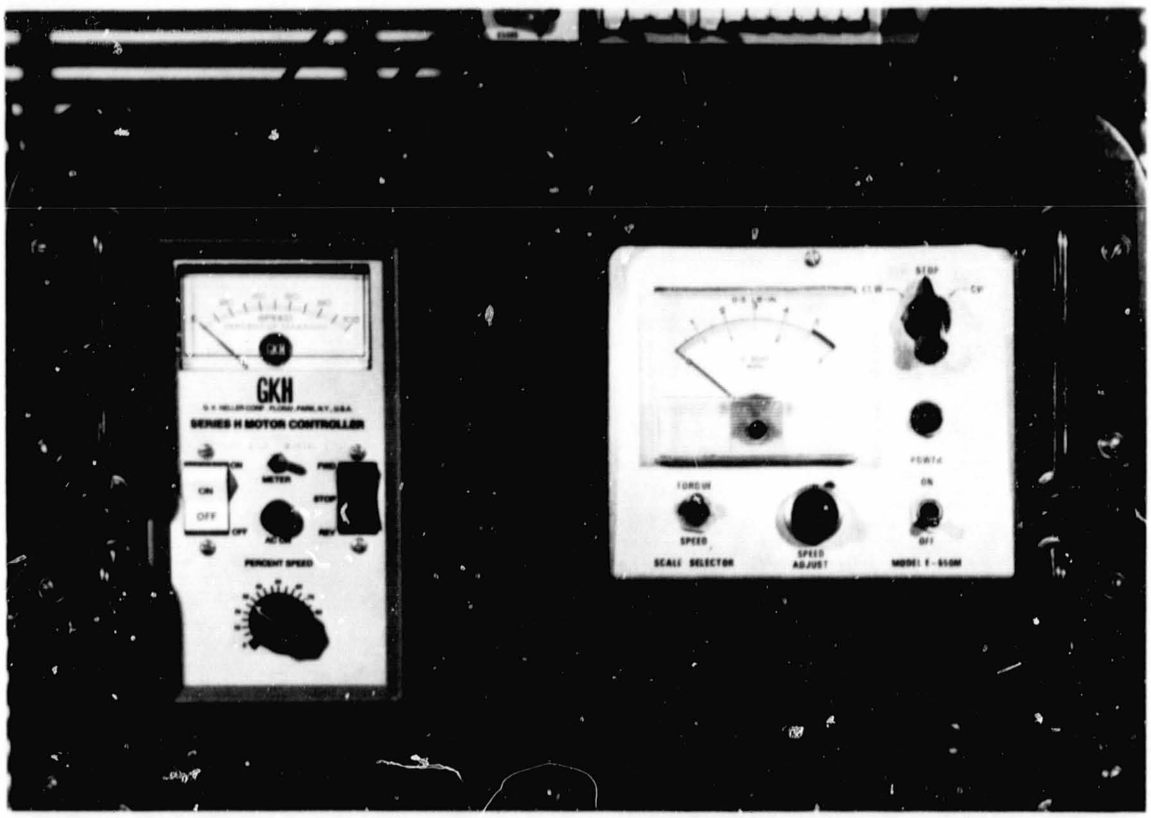
Automatic Melt-Level Control System

Improved Circuitry:

- **Utilizes existing melt replenishment system**
- **Provides continuously variable polysilicon feed rate**
- **Insensitive to changes in laser beam intensity**
- **Operation demonstrated**

Control Panel for Improved Melt Level Control

(Commercial Controller at Left)



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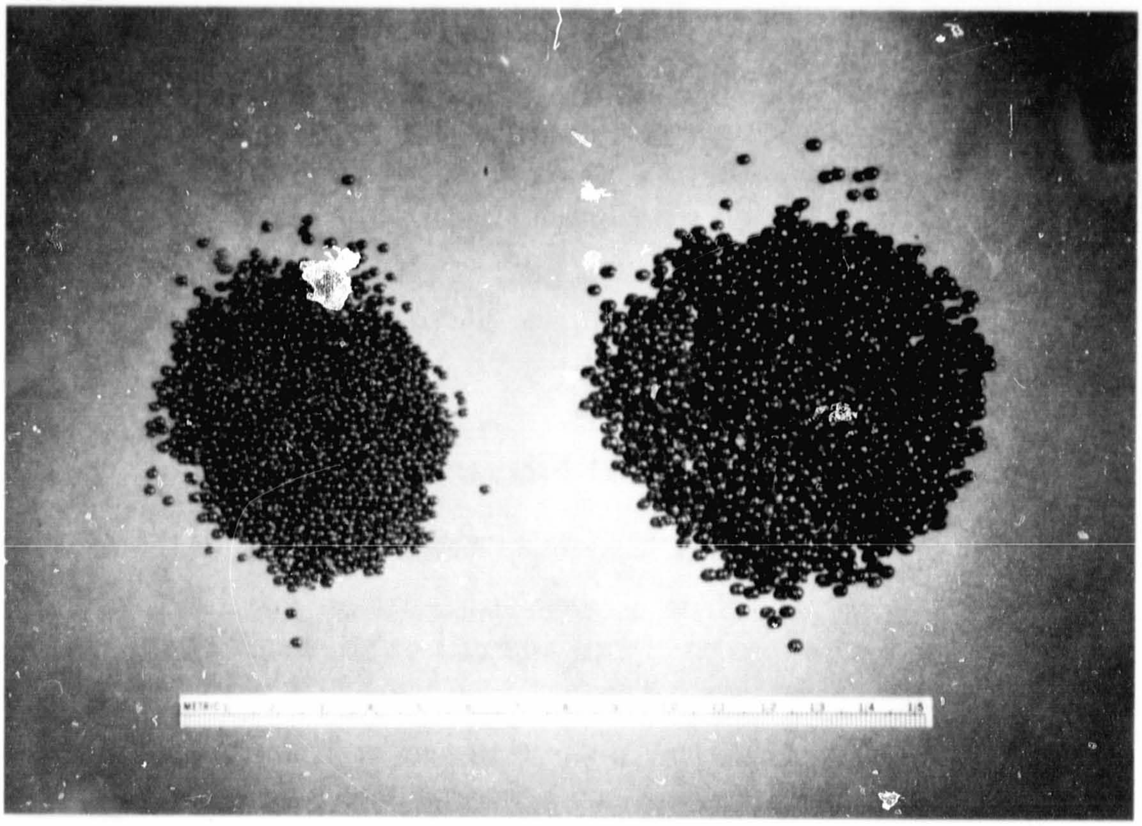
Polysilicon Pellets From Kayex Shot Tower:
Left 0.4 to 2 mm, Right 2.0 to 2.8 mm



Problems

- Long delivery time for components
- Availability of low-cost pellet-form polysilicon

Summary

All Tasks On Schedule Per Contract Requirement

- Prototype furnace design, fabrication, assembly
- Development of techniques for higher throughput

MULTIPLE RIBBON GROWTH BY EFG

MOBIL TYCO SOLAR ENERGY CORP.

1981 Goals

- DESIGN, FABRICATION AND OPERATION OF NEW EXPERIMENTAL SHEET GROWTH UNIT (ESGU), FURNACE 21, FOR GROWTH OF FOUR 10 CM WIDE RIBBONS AT 4 CM/MINUTE WITH AUTOMATIC WIDTH CONTROLS AND MELT REPLENISHMENT.

- DEMONSTRATION OF LARGE AREA (50 CM^2) CELL OF EFFICIENCY GREATER THAN 12.0%

1981 Program

MULTIPLE RIBBON FURNACES

- FURNACE 16 - TESTING OF NEW CARTRIDGE DESIGNS FOR STRESS REDUCTION, AMBIENT CONTROL, AUTOMATIC CONTROL SYSTEMS, AND UPGRADED MELT REPLENISHER.

- FURNACE 21 - NEW ESGU UNIT IS TO BE BUILT AT MOBIL TYCO EXPENSE AND INCORPORATED INTO THE PROGRAM ON NOVEMBER 1, 1981 FOR DEVELOPMENT WORK

SINGLE 10 CM CARTRIDGE FURNACES

- FURNACE 17 - OPTIMIZATION OF SPEED CAPABILITY AND QUALITY AT 4 CM/MINUTE.

- FURNACE 18 - DEVELOPMENT OF 10 CM WIDE RIBBON GROWTH WITHOUT CONVENTIONAL COLD SHOES.

CELL AND MATERIAL CHARACTERIZATION

- STUDY OF GROWTH PARAMETER, MATERIAL PROPERTY AND CELL PROCESSING INTERRELATIONSHIPS.

Ambient Effects in Multiple-Ribbon Furnace Environment

- PRELIMINARY TEST IN FURNACE 16 OF INTERFACE AMBIENT CONTROL SYSTEM DEVELOPED IN SINGLE-CARTRIDGE FURNACE 17 WAS SUCCESSFUL.

- FACTORS IDENTIFIED FOR ACHIEVING REPRODUCIBILITY:

  - CO LEVEL IN MAIN FURNACE IS HIGH AND VARIABLE WITH TIME; MAIN ZONE GASES EXIT THROUGH CARTRIDGES.

  - GAS OUTFLOW THROUGH EACH CARTRIDGE IS INDETERMINATE BECAUSE OF MULTIPLE OPENINGS.

  FUTURE WORK: DESIGN OF A GAS TIGHT RIBBON SEAL TO EXCLUDE EXTERNAL ATMOSPHERE FROM MENISCUS AREA IS COMPLETE; SEAL COMPONENTS NOW BEING PREPARED FOR TESTING.

Run Data for Multiple 10 cm Wide Ribbon Growth in Furnace 16 (Model 3A).

		Fourth Quarter 1980					First Quarter 1981
	Run Nos.:	244	247	248	249	250	254
Overall System:	Duration of growth period (minutes)	279	150	317	310	595	456
	Length of ribbon produced (meters)*	12.2	7.9	18.9	8.2	33.0	33.8
	Time percentage of simultaneous three-ribbon growth	0	15	34	0	21	47
Cartridge #1:	Length of ribbon produced (meters)	4.1	3.8	6.0	3.2	9.6	10.2
	Time percentage of run period operating	44.8	80.0	56.7	31.2	48.1	62
	Average growth rate (cm/minute)	3.25	3.17	3.30	3.27	3.36	3.59
Cartridge #2:	Length of ribbon produced (meters)	7.6	3.0	8.9	5.0	15.6	12.3
	Time percentage of run period operating	93.5	62.0	98.7	47.0	89.7	84
	Average growth rate (cm/minute)	2.92	3.22	2.81	3.40	2.92	3.20
Cartridge #3:	Length of ribbon produced (meters)	0	1.5	4.0	0	7.8	10.6
	Time percentage of run period operating		38**	47.3		47.0	72
	Average growth rate (cm/minute)		2.6**	2.63		2.78	3.21

*All listed quantities are for full-width ribbon, except cartridge #3 in run 247.

**Estimated data.

SUMMARY OF SOLAR CELL DATA FOR MULTIPLE RIBBON FURNACE RUN NO. 16-259.
GROWTH SPEED 3.5 CM/MINUTE, ρ = 1.0 Ω-CM, 6.25 CM^2 CELL AREA.
MAIN ZONE ARGON PURGE RATE 9.8 ℓ/MINUTE.
PH_3 PROCESSED; ELH LIGHT, 100 mW/CM^2, 28°C, NO AR COATING.

SINGLE CARTRIDGE OPERATION

AMBIENT GAS IN CARTRIDGE	L_D (μm)	O_i $x10^{16}$ cm^{-3}	NO. OF PIECES	CELL PARAMETERS J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η (%)
0 ℓ/m, Ar	8	*	7	11.0	0.469	0.753	3.9
0.07 ℓ/m, 1% CO_2 in Ar	30	*	3	15.9	0.511	0.751	6.1
0.15 ℓ/m, 1% CO_2 in Ar	42	ND	7	16.9	0.516	0.699	6.1
0.27 ℓ/m, 1% CO_2 in Ar	24	6.8	7	16.1	0.513	0.658	5.4

* NOT MEASURED.

ND = NOT DETECTED.

High-Speed Growth Performance: Furnace 17

- IMPACT OF DIE AND COLD SHOE DESIGN ON GROWTH STABILITY AT 4 CM/MINUTE IS UNDER EXAMINATION.
- THICKNESS UNIFORMITY AT 200 MICROMETERS (8 MILS) AND GUIDANCE/FLATNESS IMPROVEMENT STUDIES IN PROGRESS.

STATUS: GROWTH STABILITY WITH AMBIENT CONTROL IMPLEMENTATION GOOD AT 3.5 CM/MINUTE.

RIBBON FLATNESS AT 8 MILS (200 MICROMETERS) NOT SATISFACTORY ABOVE 3 CM/MINUTE DUE TO GUIDANCE AND STRESS-INDUCED BUCKLING PERTURBATIONS.

Quality Studies: Furnace 17

- PROPERTIES OF RIBBON GROWN WITH COLD SHOES RESPOND TO AMBIENT GAS CHANGES IN MUCH THE SAME WAY AS FOR RIBBON GROWN WITHOUT COLD SHOES.

- QUARTZ IN THE MELT IN GRAPHITE CRUCIBLES AND MENISCUS CO_2/O_2 HAVE SIMILAR IMPACT IN IMPROVING CELL PROPERTIES.

STATUS: CELL PERFORMANCE (10 TO 11%) FOR SYSTEM WITH COLD SHOES IS BELOW THAT OF SYSTEM WITHOUT COLD SHOES (12 TO 13%).

SUMMARY OF AVERAGED SOLAR CELL DATA FOR PHOSPHINE PROCESSED CELLS FROM RIBBON GROWTH RUN NO. 17-136, WITH CO_2 PLUS O_2 IN AMBIENT: GROWTH SPEED OF 3.1 CM/MINUTE, $\rho = 6\ \Omega$-CM.

GROWTH SEGMENT	CARTRIDGE AMBIENT	L_D (μM)	$[O]_i$ $\times 10^{-16}$	NO. OF PIECES	CELL PARAMETERS (NO AR) J_{SC} (MA/CM^2)	V_{OC} (V)	FF	EFF. (%)
1A	AR	19	-	6	15.8	0.472	0.681	5.1
2B	0.14% CO_2 + 14 PPM O_2	45	16	11	18.6	0.519	0.717	6.9
2C	0.23% CO_2 + 23 PPM O_2	34	28	12	19.2	0.524	0.746	7.5

STUDY OF HIGH CO_2 AND O_2 CONCENTRATION (> 0.5%) EFFECT ON CELL PERFORMANCE. GROWTH SPEED OF 3.5 CM/MINUTE. NOMINAL $\rho = 1\ \Omega$-CM.

RUN NO.								
17-117	AR	33	-	8	12.5	0.477	0.707	4.2
17-175	0.3% CO_2	36	7	7	16.8	0.521	0.728	6.4
17-178	0.5% CO_2 + 50 PPM O_2	35	TRACE	7	17.5	0.522	0.705	6.4
	1.0% CO_2 + 100 PPM O_2	34	TRACE	4	16.8	0.519	0.622	5.5
17-176	1.0% CO_2 + 100 PPM O_2	37	NA	9	15.7	0.508	0.686	5.5
17-177	1.0% CO_2 + 100 PPM O_2	32	NA	10	15.9	0.519	0.615	5.1

NA = NOT AVAILABLE

Quality and Stress Basic Studies: Furnace 18

- COLD SHOE IMPACT ON QUALITY AND STRESS IS UNKNOWN.
- GROWTH SPEED INFLUENCE ON QUALITY IS UNKNOWN.

THESE QUESTIONS ARE BEING ADDRESSED THROUGH DEVELOPMENT OF SYSTEM FOR GROWTH OF 10 CM WIDE RIBBON AT 3 TO 4 CM/MINUTE WITHOUT USE OF CONVENTIONAL COLD SHOES.

- GROWTH WITHOUT COLD SHOES AT 2 CM/MINUTE HAS BEEN ESTABLISHED.
- HIGHER SPEEDS SOUGHT WITH USE OF END-ONLY AND ASYMMETRIC COLD SHOES.

Construction and Operation of Furnace 21

- NEW UNIT FOR SIMULTANEOUS GROWTH OF FOUR 10 CM WIDE RIBBONS.
  - DESIGN OF FURNACE COMPLETED.
  - FABRICATION OF MAIN ZONE COMPONENTS IS NEARLY COMPLETE.
  - ASSEMBLY OF SUBSYSTEMS IS NOW UNDERWAY.
- INPUT TO 10 CM CARTRIDGE DESIGN IS TO CONTINUE UNTIL SEPTEMBER.

Summary

QUALITY

- IMPROVEMENT OF HIGH SPEED RIBBON CELL EFFICIENCIES ABOVE CURRENT 11% IS REQUIRED:
  - GROWTH PARAMETERS HAVE BEEN IDENTIFIED THAT CHANGE AS-GROWN PROPERTIES AND BEHAVIOR OF RIBBON IN PROCESSING, BUT SPECIFIC MECHANISMS ARE NOT KNOWN.

SPEED

- PRODUCTIVITY AND THROUGHPUT INCREASES REQUIRE HIGHER GROWTH SPEEDS THAT MUST BE ACHIEVED WITHOUT COMPROMISING QUALITY:
  - THE INFLUENCE OF COLD SHOES ON QUALITY AND STRESS LEVEL NOT KNOWN.
  - GUIDANCE AND BUCKLING PERTURBATIONS OF RIBBON FLATNESS AT 200 MICROMETERS (8 MILS) LIMIT PRODUCTIVITY ABOVE 3 CM/MINUTE.

Future Work: Quality

- COLD SHOE/SPEED INCREASE EFFECTS ON QUALITY:
  - DYNAMIC (MELT AND GROWTH INTERFACE) PHENOMENA INFLUENCE.
  - TEMPERATURE PROFILE, IN SITU COOLING CYCLE.
  - AMBIENT GAS-MENISCUS SURFACE REACTIONS.
  - DEFECT GENERATION BY INCREASED LEVEL OF STRESSES.
  - IMPURITY CONTAMINATION.

- <u>APPROACHES</u>
  - DEVELOPMENT AND CHARACTERIZATION OF SYSTEM FOR GROWTH WITHOUT CONVENTIONAL COLD SHOES.
  - STUDY OF MELT TRANSPORT PHENOMENA BY FINITE ELEMENT COMPUTER SIMULATION (COLLABORATION WITH MIT).
  - OPTIMIZATION OF GAS INTRODUCTION SYSTEM IN MULTIPLE AND SINGLE RIBBON FURNACES AND STUDY OF INFLUENCE OF DIFFERENT GAS SPECIES, CONCENTRATIONS AND GAS FLOW PATTERNS.
  - MATERIAL PROPERTY (RESISTIVITY, OXYGEN LEVEL) STUDIES COMPARING LOW AND HIGH SPEED GROWN RIBBON.

Future Work: Productivity

- COLD SHOE/SPEED INCREASE EFFECTS ON PRODUCTIVITY:
  - STRESS AND BUCKLING CHARACTERIZATION
  - GROWTH STABILITY AT 4 CM/MINUTE

- APPROACHES
  - COMPARISON OF RIBBON STRESS/BUCKLING LEVELS WITH AND WITHOUT CONVENTIONAL COLD SHOES.
  - TESTING OF MODIFIED TEMPERATURE PROFILES IN POST-GROWTH ENVIRONMENT.
  - DESIGN WORK WITH NEW DIES, COLD SHOES.
  - GROWTH IN MULTIPLE RIBBON FURNACE 21 WITH ONE OPERATOR TO EXAMINE 12 RIBBON PER OPERATOR ESGU GROWTH CONCEPT.

ADDED CONSTRAINT: SPEED AND PRODUCTIVITY INCREASES MUST BE CONSISTENT WITH MAINTAINING OF GOOD QUALITY LEVEL.

- IT IS THEREFORE NECESSARY TO HAVE CONCURRENT RIBBON PROPERTY STUDIES AND BASIC MATERIAL CHARACTERIZATION AND CELL PROCESSING EFFORT .

ADVANCED CZOCHRALSKI INGOT GROWTH

KAYEX CORP.

R.L. Lane

This report on Contract 955733 is titled "Advanced Czochralski Ingot Growth for Technology Readiness."

The contract work started October 1, 1980, and was first scheduled for completion 13 months later on November 1, 1981. Subsequently, at the request of JPL, the program plan was extended five months for a new completion date of March 31, 1982, to minimize current fiscal year expenditures.

All references to program plan and status will be made on the revised schedule, which became effective May 1, 1981.

Presentation Format

1. OBJECTIVES OF CONTRACT
2. APPROACH
3. PROGRAM PLAN
4. PRESENT STATUS
5. AREAS OF CONCERN
6. PLANS

This is the presentation format I will follow. After stating the contract objectives, I will describe our approach to achieving these objectives.

The program plan will describe how we have broken down the project into separate tasks. Although the program plan does illustrate current status, I will elaborate considerably on our status in this presentation.

There are certain areas of concern, or problems, which present obstacles to the achievement on our status in this presentation.

Finally, I will describe our plans for the balance of the contract and what we hope to achieve.

Goals

- GROWTH OF 150 KG OF INGOTS FROM ONE CRUCIBLE USING PERIODIC MELT REPLENISHMENT
- DIAMETER - 15 CM
- THROUGHPUT - 2.5 KG/HR
- RECHARGE MELTING RATE - 25 KG/HR
- AFTER GROWTH YIELD - 90%
- MICROPROCESSOR CONTROLS PLUS IMPROVED SENSORS FOR MELT TEMP, INGOT DIAMETER, AND MELT LEVEL
- PROTOTYPE EQUIPMENT SUITABLE FOR HIGH VOLUME SILICON PRODUCTION, TRANSFERABLE DIRECTLY TO INDUSTRY

Of course, the whole effect is designed to reduce the add-on cost of ingot growth.

We have, in the past, established that 100 kilograms can be grown from one crucible (using semiconductor-grade poly) and that the efficiency of the last material produced is the same as the first, provided single-crystal structure is achieved. (Loss of single crystallinity degrades solar efficiency somewhat.)

Also, we have achieved up to 88% of high-quality single-crystal ingot from 100-kilogram runs.

In this program, we have increased the goal to 150 kilograms and the diameter to 15 centimeters in an attempt to reduce the cost further.

Additional cost savings, however, will not come from even larger quantities. (Indeed, the add-on cost per kilogram is essentially flat as you approach 150 kilograms.) Cost improvements will now come from improvements in throughput and process parameter control, yields, automation and equipment performance.

-- A significant portion of this project is devoted to understanding the process parameters as they relate to yields and throughput.

-- Yield improvement means more material per run that meets the required solar efficiency.

-- Automation improvement means not only reduced labor, but consistent product.

-- Equipment can impact cost by performing more reliably with less down-time.

The equipment that has been designed and built on this project has a large number of inprovements, specifically addressing the needs and requirements for the production of large quantities of ingot material.

Approach

- CONSTRUCT AN IMPROVED CRYSTAL GROWER HAVING THE PERFORMANCE REQUIRED TO ACHIEVE GOALS
- CONSTRUCT AN AUTOMATED SYSTEM WHICH WILL OFFER RELIABLE PERFORMANCE LEADING TO IMPROVED YIELDS AND REDUCED LABOR COST
- CONDUCT PROCESS DEVELOPMENT ON LARGE SIZE CRYSTAL GROWTH, MELT REPLENISHMENT AND IMPROVED THROUGHPUT AND YIELDS
- CONDUCT A PARALLEL ANALYTICAL PROGRAM TO HELP UNDERSTAND THE PROCESS

Kayex personnel continue to believe that there are a number of areas in conventional Cz that can be cost-improved. In our approach, we started first by constructing improved equipment.

Long runs, lasting 60 to 100 hours, multiple recharge cycles, large ingots up to 50 kilograms requiring up to 60 kilograms of melt, all require special consideration in equipment design.

The JPL facility design has incorporated these improvements. Improved areas include seals, sectional furnace chambers, increased capacity, longer-life graphite designs, additional sight ports for sensors and the like.

All these improvements have been reported in detail previously and are expected to help achieve the improved cost goals.

The growth facility also is controlled with a microprocessor-based programmable controller. This will result in significant cost benefits relating to labor, throughput, yields, etc. The controller is easily programmed on the factory floor by a supervising engineer for the particular material being produced or process required.

The equipment is the tool; however, process development is required to demonstrate what can be achieved with the tool. The process development task will identify important variables and attempt to optimize them. Specifically, we will attempt to demonstrate improved throughputs and yields.

The analytical program is being conducted in support of the process development task for the purpose of better understanding of the process.

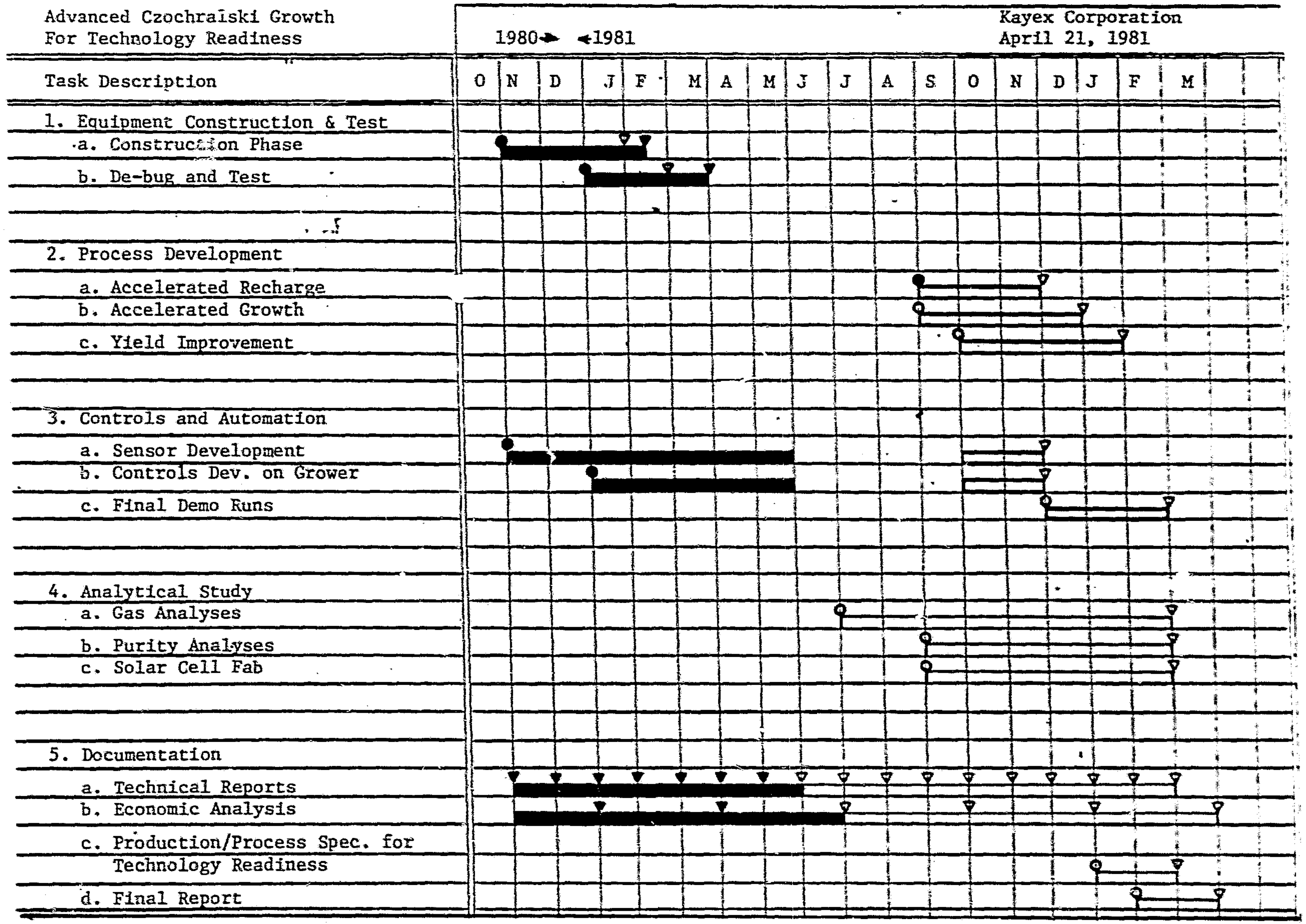
Here, the main approach is to:

(1) Conduct crucible and silicon purity analyses

(2) Fabricate and evaluate solar cells prepared from grown ingots

(3) Analyze furnace gas atmosphere (CO, CO_2, H_2O, etc.) and correlate the results with crucible performance and ingot quality.

Program Plan, Rev. 2



LARGE-AREA SILICON SHEET TASK

LARGE-AREA SILICON SHEET TASK

This plan, dated April 21, 1981, reflects the recent schedule change, but includes all of the original tasks.

It shows that the crystal grower was completed nearly to schedule plan.

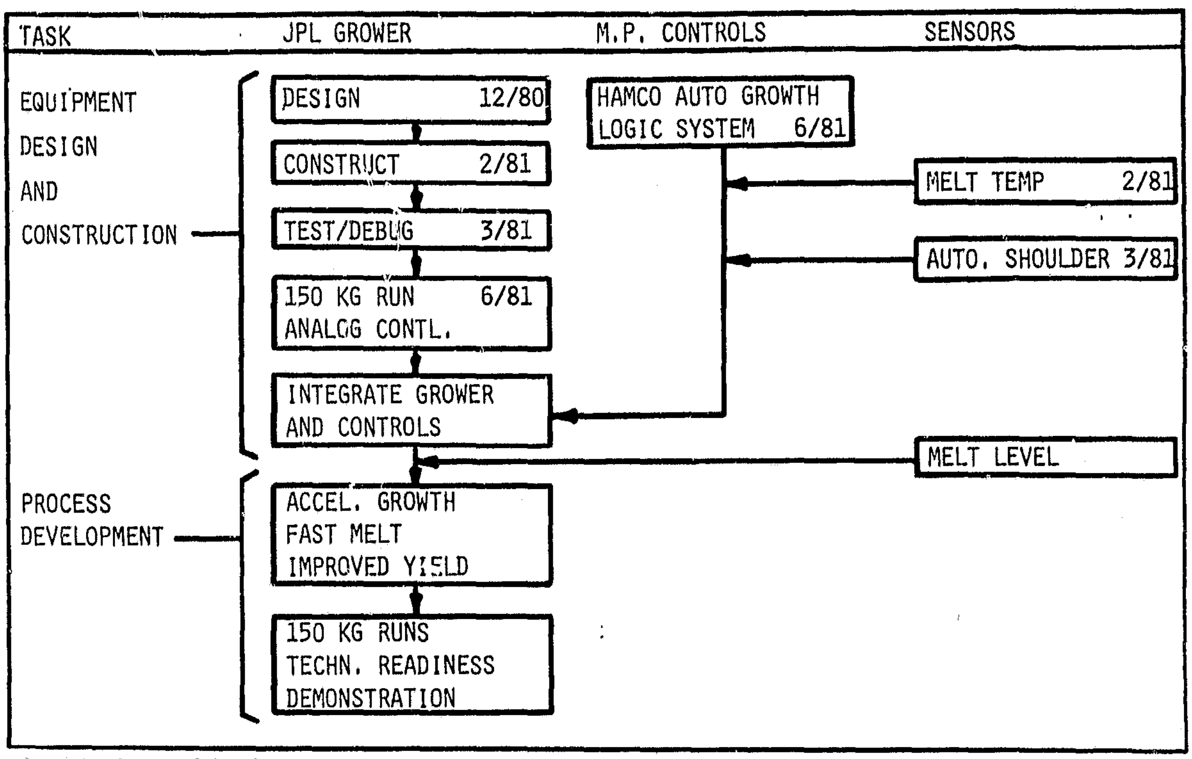
A number of single-ingot runs have been made and one 150-kilogram run was recently completed. This run was performed to establish that the equipment was totally functional for the process development work to be performed subsequently.

The simultaneous program on sensor development was conducted up to the present on another grower (a standard Hamco CG2000).

Although the program plan reflects the substantial reduction of effort for the current fiscal year, we are doing some preparatory work in anticipation of completion of the contract.

This is specifically in the area of gas analysis. We now have a completed gas chromatography system capable of measuring CO in the exhaust gas. We believe determination of CO in the furnace atmosphere to be indicative of the condition of the furnace and the reactions taking place during growth. This system is functional now and preliminary calibrations and CO measurements have been performed on one growth run.

Purity analyses, solar cell fabrication and further sensor development work have been postponed until later in the program.



START DATE: 9/21/80

This program block diagram illustrates a little better where we are in the program and how the various tasks relate to the overall projects.

Dates in the blocks indicate the date of milestone completion.

I have already indicated that the JPL grower is now complete and functional and that the first 150-kilogram run has been performed on it.

We are now preparing to install the microprocessor control system on the grower. That will be complete this month.

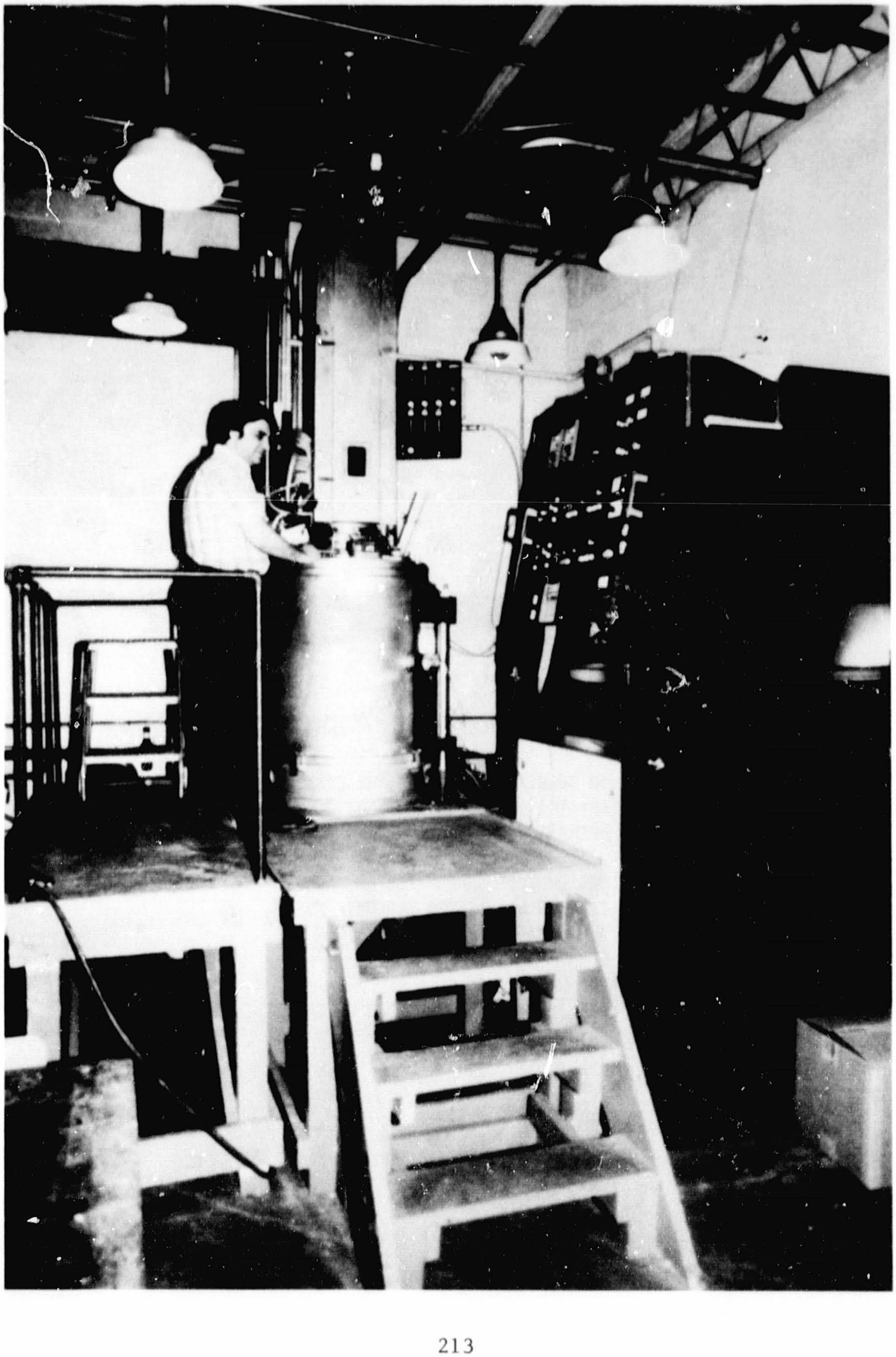
With regard to sensors, we have demonstrated automatic melt temperature trim (before seeding) and automatic shouldering on 10-centimeter-diameter crystals using a standard CG2000 machine. The software for these sensors has been incorporated in the microprocessor program and is ready for tests on large-diameter crystals and large charge melts.

Automatic melt level control will be integrated in the system later in the program.

We are now just beginning the key portion of the program: the process development task. Here we hope to be able to demonstrate faster throughput and improved yields. This involves a number of experiments relating to crucible performance, gas-flow control, and a radiation shield to assist in heat transfer from the crystal.

Finally, the technology readiness demonstration will consist of a number of 150-kilogram runs.

Gas Analysis System

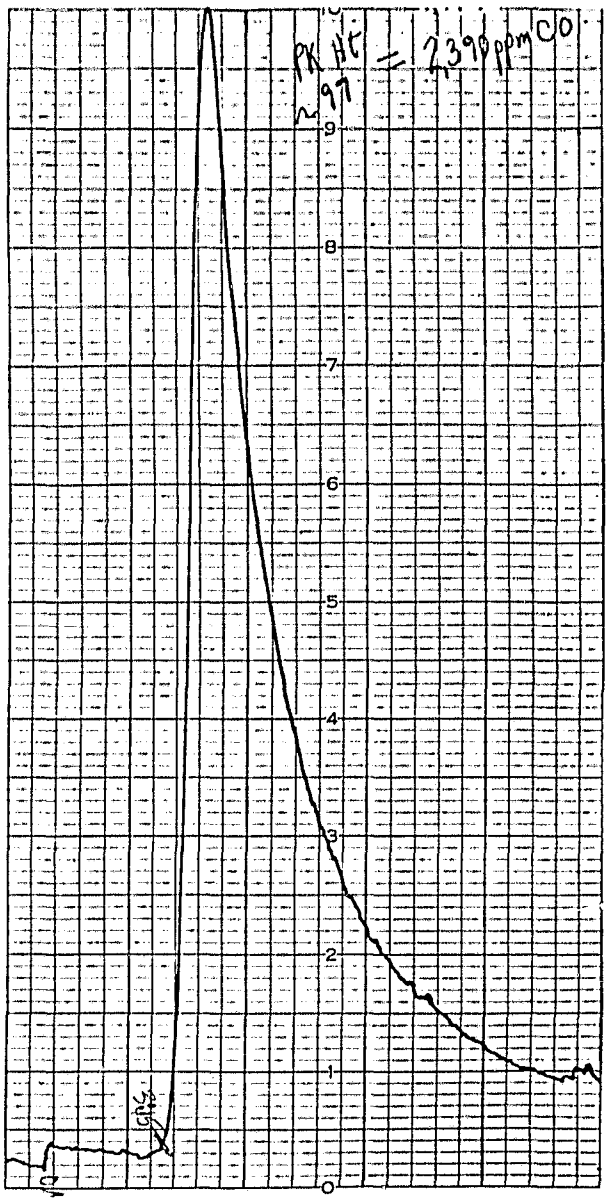


150-kg Run on JPL Growth Facility (Five 30-kg Ingots)

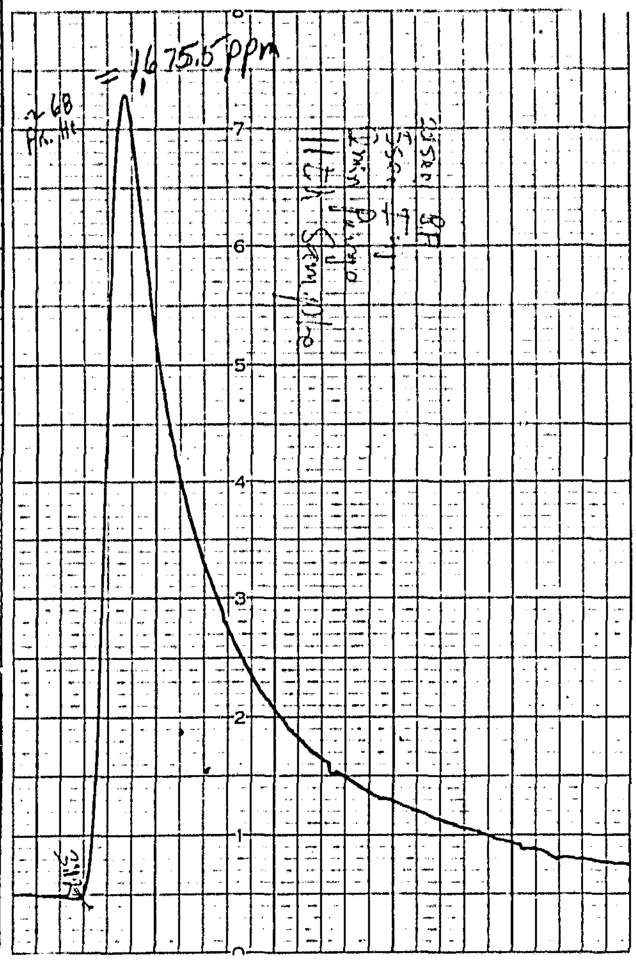
Gas Analysis Task: Objective, Approach and Status

OBJECTIVE	-	TO QUANTITATIVELY ANALYSE GASEOUS COMPONENTS OF THE CRYSTAL GROWTH ENVIRONMENT DURING GROWTH. OPERATING PRESSURE, 7.6 TORR (1/100 ATM)
APPROACH	-	GAS CHROMATOGRAPHY FOR CO AND H_2 CALCIUM STABILIZED ZIRCONIA FOR O_2 ALUMINUM OXIDE HYGROMETER FOR H_2O
STATUS	-	GCA OPERATING PRELIMINARY MEASUREMENTS OF CO OBTAINED O_2 AND H_2 ON HOLD UNTIL FY 82

Typical CO Analysis With Gas Chromatography System



CALIBRATION PEAK



CRYSTAL GROWTH RUN

Kayex Automatic Grower Logic: Implementation and Functions

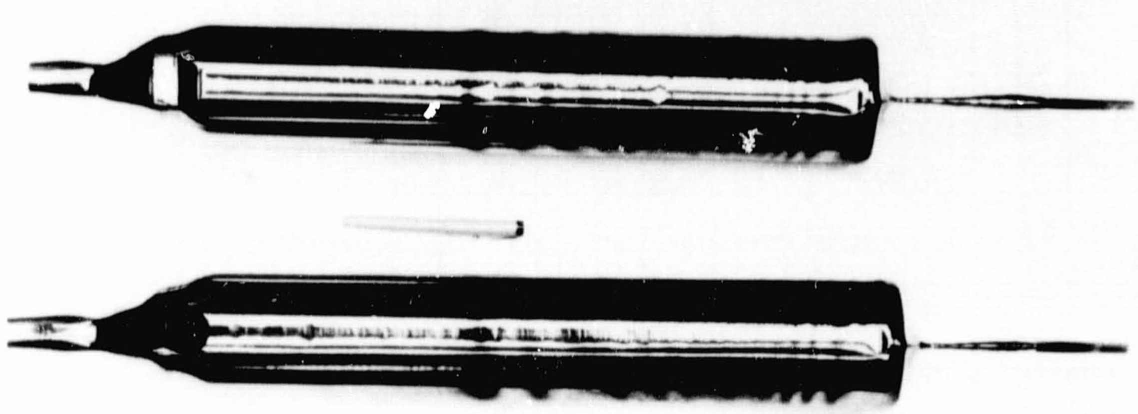
IMPLEMENTATION

- DIGITAL CONTROLLERS FOR DIAMETER, TEMPERATURE, GROWTH
- PROCESS RECIPES
- CRITICAL DECISIONS BY OPERATOR
- PARAMETERS CONTROLLED BY COMPUTER

FUNCTIONS

- MELTDOWN - RECIPE CONTROL, TERMINATED BY OPERATOR
- STABILIZATION TO SEEDING TEMP - CLOSED LOOP
- NECK GROWTH - RECIPE CONTROL, TERMINATED BY OPERATOR
- CROWN AND SHOULDER - FULLY AUTOMATIC, RECIPE, AND SENSOR
- BODY - CLOSED LOOP DIAMETER AND GROWTH RATE CONTROL
- FINAL TAPER - AUTOMATIC START, RECIPE

100-mm 10-kg Crystals Grown With Hamco AGL System



Project Status

ADVANCED CZOCHRALSKI FOR TECHNOLOGY READINESS

TASK	STATUS
EQUIPMENT DESIGN AND CONSTRUCTION	COMPLETE
GCA DESIGN AND CONSTRUCTION	COMPLETE
150 KG QUALIFICATION RUN	COMPLETE
AGL CONTROLS	INTERFACE TO JPL GROWER 7/81
SENSORS	
MELT TEMP	DEMONSTRATED ON 10 KG MELT
AUTO SHOULDER	DEMONSTRATED ON 100 MM DIAM
MELT LEVEL	SCHEDULE COMPLETION 11/81
PROCESS DEVELOPMENT	ONGOING
ANALYTICAL STUDY	ONGOING

AREAS OF CONCERN	PLANS
- YIELD OF QUALITY INGOT	- CORRELATE FURNACE ATMOSPHERE TO INGOT QUALITY AND CRUCIBLE PERFORMANCE
- CRUCIBLE DEGRADATION	- CRUCIBLE PURITY ANALYSES
- GROWTH RATE IMPROVEMENT	- INSTALL RADIATION SHIELD

UBIQUITOUS CRYSTALLIZATION PROCESS

SEMIX INC.

Thomas P. Rosenfield

$2.80/$W_p$ Commercial Readiness

SAMIS Results

PLANT CAPACITY: 10 MW/YEAR

		$/WP
SILICON ($56/KG)		0.939
CRYSTALLIZATION VALUE-ADDED		0.26
BRICK FINISHING VALUE-ADDED		0.04
WAFERING VALUE-ADDED		0.39
WAFER RINSE VALUE-ADDED		0.006
QUALITY ASSURANCE VALUE-ADDED		0.014
	TOTAL $/WP	1.649

Goals

1. DEMONSTRATION OF $2.80/WP COMMERCIAL READINESS DEPARTMENT OF ENERGY GOAL.

2. DEMONSTRATION OF $0.70/WP TECHNOLOGY READINESS DEPARTMENT OF ENERGY GOAL.

Status

1. SEMIX HAS DEMONSTRATED TO THE SATISFACTION OF JPL AND DOE THAT TARGET TECHNOLOGY PROJECTIONS CAN BE MET FOR THE COMMERCIAL READINESS GOAL AND WILL PROCEED TOWARD THE $2.80/WP TARGET WITH INTERNAL FUNDS.

2. THE COOPERATIVE AGREEMENT HAS BEEN RESCOPED TO FOCUS ON THE BASIC CRITICAL TECHNOLOGY ELEMENTS NECESSARY TO DEMONSTRATE TECHNICAL FEASIBILITY FOR $0.70/WP.

Demonstration Parameters

TECHNOLOGY

UBIQUITOUS CRYSTALLIZATION PROCESS TO YIELD SILICON SHEET	PHASE I COMPLETION DATE: 6/19/81 REPORT DATE : 7/15/81

GOALS:	STATUS:
1. CRYSTALLIZATION:	1. CRYSTALLIZATION:
o BATCH PROCESS	o BATCH PROCESS
o BRICK SIZE: 30 x 30 x 20 CM	o BRICK SIZE: 20 x 20 x 15 CM
o PROCESS YIELD: 99%	o 95%
o .5 MACHINE/OPERATOR	o 3.0 MACHINES/OPERATOR
2. WAFERING:	2. WAFERING:
o WAFER AREA: 100 CM^2	o DEMONSTRATED 100 CM^2
o .584 MM CENTER TO CENTER	o .597 MM CENTERS (ID) o .610 (MBS)
o PROCESS YIELD: 98%	o 95% (ID) 99+% (MBS)
o 4 MACHINES/OPERATOR	o 6 MACHINES/OPERATOR (MBS)
3. GENERAL:	3. GENERAL:
o SILICON UTILIZATION: .64 M^2/KG	o >.50 M^2/KG.
o AM1 CELL EFFICIENCY: 12%	o OVER 3000 CELLS VERIFIED AT 11-12% FOR 100 CM^2 17% FOR 2 x 2 CM

Average Energy Consumption

PROTOTYPE 1

CRYSTALLIZATION DATES	NO. OF RUNS	ENERGY USAGE* (KWHR/KG OF SI) MELTING	CRYSTALLIZATION	UCP** YIELD
SEP. 20 - OCT. 19	10	20	5	99%
OCT. 20 - NOV. 19	16	14	6	94%
NOV. 20 - DEC. 19	20	12	7	98%
TOTAL	46	15	6	96%

PROTOTYPE 2

CRYSTALLIZATION DATES	NO. OF RUNS	ENERGY USAGE* (KWHR/KG OF SI) MELTING	CRYSTALLIZATION	UCP** YIELD
NOV 4 - NOV 19	11	6	7	96%
NOV 20 - DEC 19	21	5	7.7	90%
TOTAL	32	6	7	93%

*VALUES ARE AVERAGED FOR THE NUMBER OF RUNS DURING THE SPECIFIED TIME PERIOD.

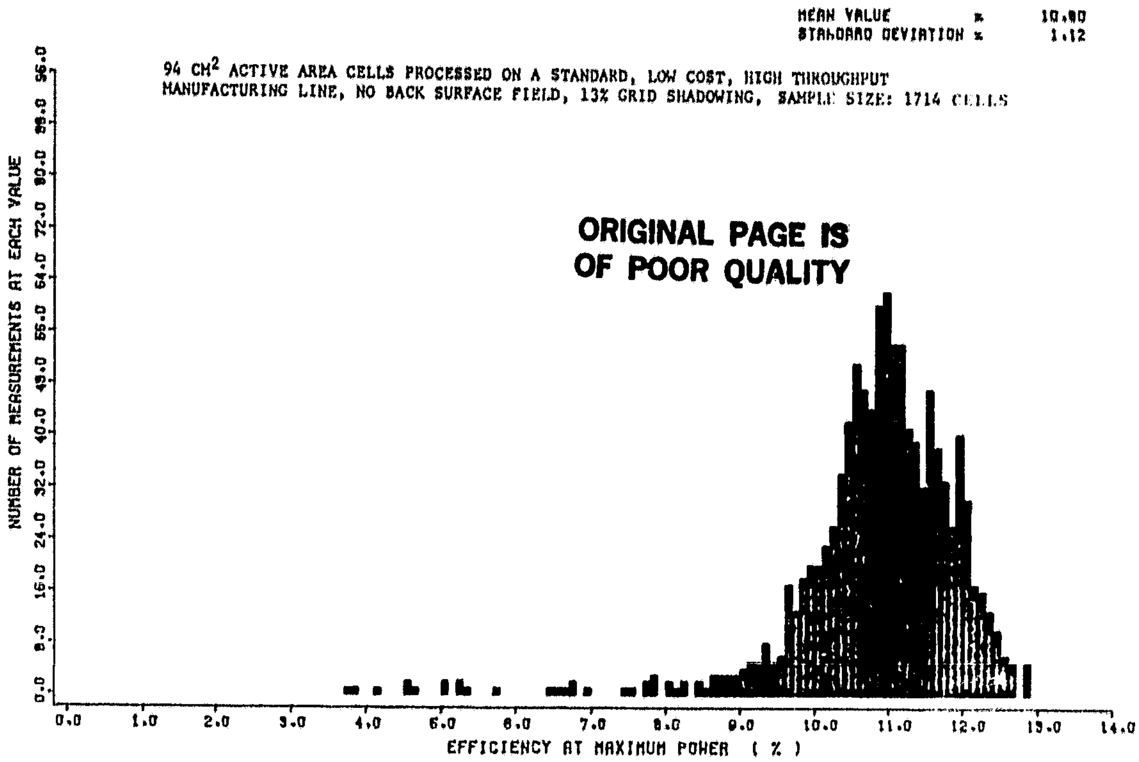
**UCP YIELD = USABLE BRICK WEIGHT/CHARGE WEIGHT X 100.

Status of Wafering: Simultaneous Experimental Results

(Best to Date)

	MBS	MBS II	ID
PROCESS YIELD, %	95	98	95
MATERIAL YIELD, M^2/KG	.70	.63	.72
WAFER SIZE, MM	100 x 100	100 x 150	100 x 100
WAFER THICKNESS, MM (INCH)	.330 (.013)	.356 (.014)	.292 (.0115)
KERF LOSS, MM (INCH)	.279 (.011)	.330 (.013)	.305 (.012)
RUN TIME (MBS), HR:MIN OR CYCLE TIME (ID), MIN	28:00	14:00	2.5
MACHINE OUPUT, M^2/HR	.11	.29	.24

Distribution of Measured Values of Efficiency



$0.70/$W_p$ Technical Feasibility SAMIS Results

PLANT CAPACITY 100 MW/YEAR

	$/WP
SILICON	0.1726
CRYSTALLIZATION VALUE-ADDED	0.0110
BRICK FINISHING VALUE-ADDED	0.0032
QUALITY ASSURANCE VALUE-ADDED	0.0003
WAFERING VALUE-ADDED	0.0976
WAFER RINSE VALUE-ADDED	0.0003
SHIPPING VALUE-ADDED	0.0012
TOTAL $/WP	0.2862

JPL PRICE ALLOCATION: $0.37/WP

Technical Feasibility
Demonstration

100 MWP/YEAR CAPACITY

TECHNOLOGY

UBIQUITOUS CRYSTALLIZATION PROCESS TO YIELD SILICON SHEET

COMPLETION DATE: 6/19/84
REPORT DATE : 7/15/81

GOALS:	STATUS:
1. CRYSTALLIZATION:	1. CRYSTALLIZATION:
o CRYSTALLIZATION RATE: 2.5 KG/HR	o 2.5 KG/HR
o BRICK SIZE: 30 X 30 X 19 CM	o BRICK SIZE 20 X 20 X 15 CM
o PROCESS YIELD: 99%	o TO BE DEMONSTRATED
o 1 MAN/MACHINE	o TO BE DEMONSTRATED
o AUTOMATED CONTROLS	o UNDER DEVELOPMENT
2. WAFERING:	
A. INTERNAL DIAMETER	
o 100 X 150 X .227 MM	o 100 X 100 X .292 MM*
o .454 MM CENTERS	o .592 MM CENTERS
o THROUGHPUT RATE: .3 M^2/HR.	o .24 M^2/HR.
o PROCESS YIELD: 95%	o 95%
o 12 MACHINES/MAN	o 6-13 MACHINES/MAN DEMONSTRATED IN THE INDUSTRY
B. HIGH SPEED MULTI-BLADE SLURRY	
o 100 X 150 X .254 MM	
o .508 MM CENTERS	
o THROUGHPUT RATE: 1.0 M^2/HR.	PROPRIETARY
o PROCESS YIELD: 95%	
o 4 MACHINES/MAN	
3. GENERAL:	
o OVERALL SILICON UTILIZATION: .81 M^2/KG	o >.50 M^2/KG.
o AM1 CELL EFFICIENCY: 15% 10 X 15 CM	o 11-12% 10 x 10 CM 17% 2 X 2 CM

* 120 X 160 X .343 MM WAFERS HAVE BEEN DEMONSTRATED.

Technical Strategy
Crystallization

ELEMENTS	STATUS 6/19/81	PHASE II 6/19/82 GOALS	PHASE III 6/19/83 GOALS	PHASE IV 6/19/84 TECHNICAL FEASIBILITY DEMONSTRATION
1. BRICK SIZE	23 x 23 x 14 CM 17.4 KG	31 x 31 x 19 CM 42.5 KG	30.6 x 30.6 x 19 41.5 KG	30.3 x 30.6 x 19 41 KG
2. CRYSTALLIZATION RATE	2.5 KG/HR	2.5 KG/HR	2.5 KG/HR	2.5 KG/HR
3. CONTROLS	ANALOG	PROGRAMMED CONTROLS DESIGNED	PROGRAMMED CONTROL	PROGRAMMED CONTROL
4. PROCESS YIELD	95%	97%	98%	99%

LARGE-AREA SILICON SHEET TASK

Wafering

ELEMENTS	STATUS 6/19/81	PHASE II 6/19/82 GOALS	PHASE III 6/19/83 GOALS	PHASE IV 6/19/84 TECHNICAL FEASIBILITY DEMONSTRATION
ID MACHINE	22"	27"	27"	27"
1. WAFER SIZE, MM (IN)	100 x 100 x .292 (.115)	100 x 100 x .254 (.010)	100 x 150 x .227 (.009)	100 x 150 x .227 (.009)
2. KERF LOSS, MM (IN)	.305 (.012)	.279 (.011)	.254 (.010)	.227 (.009)
3. OUTPUT, M^2/HR	.24	.3	.3	.3
4. MATERIALS YIELD, M^2/KG	.72	.80	.89	.94
5. PROCESS YIELD, %	95	95	95	95
MBS MACHINE	HIGH SPEED	HIGH SPEED	HIGH SPEED	HIGH SPEED
1. WAFER SIZE, MM (IN)	100 x 100 x .381 (.015)	100 x 100 x .279 (.011)	100 x 150 x .279 (.011)	100 x 150 x .254 (.010)
2. KERF LOSS, MM (IN)	.330 (.013)	.279 (.011)	.279 (.011)	.254 (.010)
2. OUPUT, M^2/HR	.59	.63	1.0	1.0
4. MATERIALS YIELD, M^2/KG	.60	.77	.77	.84
5. PROCESS YIELD, %	90	95	95	95

Process and Materials Performance

ELEMENTS	STATUS 6/19/81	PHASE II 6/19/81 GOALS	PHASE III 6/19/83 GOALS	PHASE IV 6/19/84 TECHNICAL FEASIBILITY DEMONSTRATION
1. OVERALL SILICON MATERIAL UTILIZATION	>.50 M^2/KG	.65 M^2/KG	.75 M^2/KG	.81 M^2/KG
2. CELL PERFORMANCE (AM1)	11 - 12% 10 x 10 CM 17% 2 x 2 CM	13 - 14% 10 x 10 CM	15% 10 x 10 CM	15% 10 x 15 CM

MAJOR DEVELOPMENT FOCUS:

- THROUGHPUT OF LARGE BRICKS AT 100 MW/YEAR
- 15% 10 X 15 CM CELLS
- .018" CENTER-TO-CENTER SPACING FOR ID TECHNOLOGY
- 9 MIL KERF LOSS ON LARGE (27") BLADES
- MAINTAINING HIGH CUTTING RATE WITH THIN WAFERS
- HIGH-THROUGHPUT MATERIAL EVALUATION TECHNIQUES

SEMIX MATERIAL JPL EVALUATION PLAN

JET PROPULSION LABORATORY

Purpose

- PROVIDE TECHNICAL DATA FOR PROGRAM MANAGEMENT
- INCREASE JPL UNDERSTANDING OF SOLAR CELL PERFORMANCE OF UNCONVENTIONAL SILICON
- AID CONTRACTOR IN MAXIMIZING PERFORMANCE
- PROVIDE PRELIMINARY INFORMATION TO PV INDUSTRY ON PERFORMANCE OF THE FUTURE SHEET

Material Received by JPL

THRU 7/1/81

• 100 SOLAR CELLS	10cm x 10cm
• 200 AS SAWN WAFERS	10cm x 10cm
• 2 INGOTS	10cm x 10cm x 12cm

Performance Evaluation

CELLS (SEMIX):

- MUTUALLY ACCEPTABLE MEASUREMENT TECHNIQUE HAS BEEN ESTABLISHED
- PRESENT BARE CELL PERFORMANCE ON 10 x 10cm CELLS IS 11 - 12% AM1 (10 CELLS)
- LARGER NUMBER OF CELLS (90) ARE IN MEASUREMENT PROCESS
- PERFORMANCE EVALUATION WILL CONTINUE ON A PERIODIC BASIS

CELL PROCESSING SHEET:

- BASE LINE CELLS 2 x 2CM PRODUCED BY ASEC

- ENHANCED PROCESS CELLS (2 x 2CM) PRODUCED BY SEMIX FROM JPL MATERIAL

- ENHANCED PROCESS CELLS (2 x 2CM) PRODUCED BY ASEC

- ENHANCED PROCESSING TO CONTINUE AS DIRECTED BY JPL/SEMIX

- MATERIAL QUALITY EVALUATION WILL CONTINUE ON PERIODIC BASIS

SHEET: *

- SPECTRAL RESPONSE
- LOCAL ELECTRICAL ACTIVITY; LIGHT SCAN, EBIC
- DIFFUSION LENGTH
- DLTS
- LOCAL CHEMISTRY/STRUCTURE

  SIMS
  O_2, C
  SEM
  TEM
- OTHER

* SPECIFIC SAMPLES SELECTED FROM PROCESSED 2 x 2CM CELLS AS REPRESENTING GOOD, AVERAGE, POOR, AND "INTERESTING" SAMPLES.

SHEET:

- RESISTIVITY DISTRIBUTION

- MECHANICAL PROPERTIES

- GENERAL ASPECTS OF CHEMISTRY

- GENERAL STRUCTURE

INGOTS:

- WAFERING CHARACTERISTICS

- DISTRIBUTION OF PERFORMANCE

Baseline Performance

ASEC RESULT:

- 10 x 10 cm WAFERS AS SUPPLIED WERE CUT INTO 16 2 x 2 cm PIECES

  12 - 15 CELLS PER INITIAL WAFER*

  MEAN FOR EACH INITIAL WAFER VARIED FROM 10.3 TO 11.0%; S.D. FROM .4 TO .7

  GRAND MEAN WAS 10.7%; S.D. WAS .3

  3 Cz CONTROL - CELLS MEAN WAS 13.1%, S.D. = .1

  ALL RESULTS @ 28°C

SEMIX/JPL RESULTS

- 10 x 10 cm CELLS AS SUPPLIED WERE MEASURED BY SEMIX AND JPL

  SEMIX - 11.6%; S.D. = .3 @ 26°C

  JPL - 11.3% S.D. = .13 @ 22°C

*ONE SHUNTED CELL WAS REJECTED AND OMITTED FROM RESULTS

INGOT CASTING: HEAT EXCHANGER METHOD (HEM)

CRYSTAL SYSTEMS INC.

F. Schmid and C. P. Khattak

Characterization of Two HEM Ingots

CONCLUSIONS:

1. RESISTIVITY IS VERY UNIFORM THROUGHOUT THE INGOT.
2. OXYGEN CONCENTRATION VARIES 3-33 PPMA.
   NO CORRELATION WITH EFFICIENCY.
3. OVERALL EFFICIENCY IS 85% OF CONTROL CELLS.
4. LARGE GRAIN POLYCRYSTALLINE HEM MATERIAL IS COMPARABLE TO SINGLE CRYSTAL HEM.
5. LARGE SiC PRECIPITATES (50-100 μM) MAY BE LIMITING SOLAR CELL EFFICIENCY.
6. HIGH DISLOCATION DENSITY (10^6/CM^2).

PROBLEM	SOLUTION
1. SIC PRECIPITATES	BACK STREAMING OF OIL VAPORS CHANGE TRAP AND MECHANICAL PUMP.
2. HIGH DISLOCATION DENSITY	CHANGE COOLDOWN CYCLE.

Best Simultaneous Achievement

INGOT SIZE	-	36 KG
SOLIDIFICATION TIME	-	18.5 HOURS
TOTAL CYCLE TIME (EST.)	-	51.5 HOURS

IPEG Analysis: HEM

INGOT SIZE	-	36.6 KG 9 BARS (10 CM X 10 CM X 15 CM)
LABOR	-	$9/HOUR 4.7 PERSONS FOR 3 SHIFT OPERATION 345 WORKING DAYS
SECTIONING ADD-ON	-	$1.09/KG
SHEET CONVERSION	-	1 M^2/KG

	ESTIMATE	ALLOCATION FOR GOAL
EQUIPMENT COST, $	35,000	42,240
FLOOR SPACE PER UNIT, SQ.FT.	60	
LABOR, UNITS/OPERATOR	10	8.5
CYCLE TIME, HRS.	56	60
EXPENDABLES/RUN, $	135	152
ADD-ON PRICE, $/$M^2$	17.39	
ADD-ON GOAL, $/$M^2$	18.15	

MATERIAL EVALUATION

APPLIED SOLAR ENERGY CORP.

1. HEM (CRYSTAL SYSTEM)

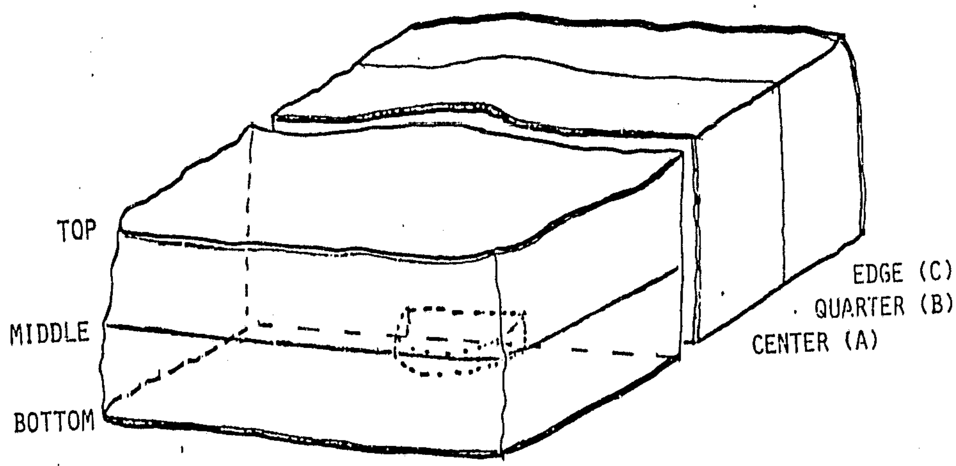
   A. HEM I.D. 41-41C

   B. HEM I.D. 41-48

2. DENDRITIC WEB (WESTINGHOUSE)

   PRE-CHARACTERIZED WAFERS

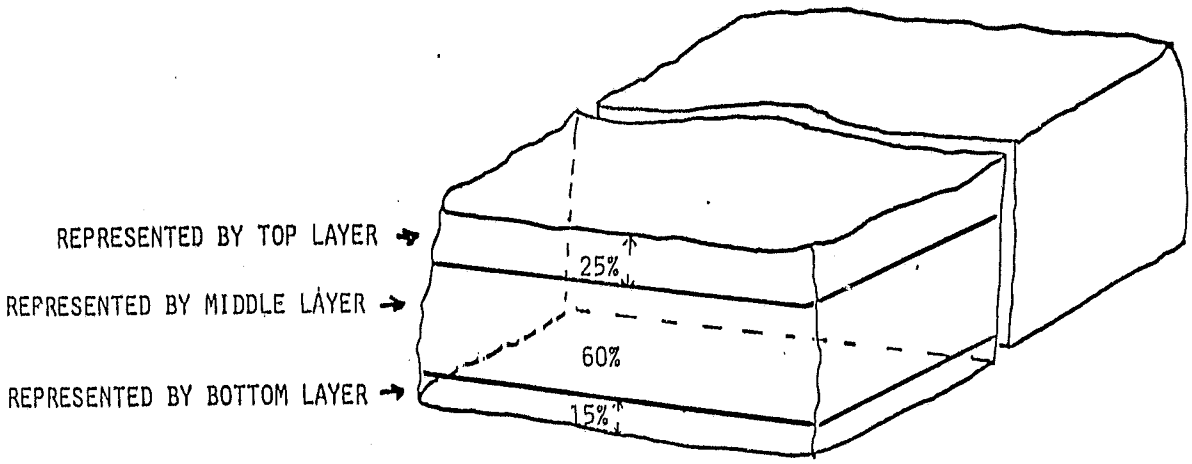
Wafer Identification Within the HEM Ingot



SIZE: 12" X 12" X 6"

WT. ~ 35 kg

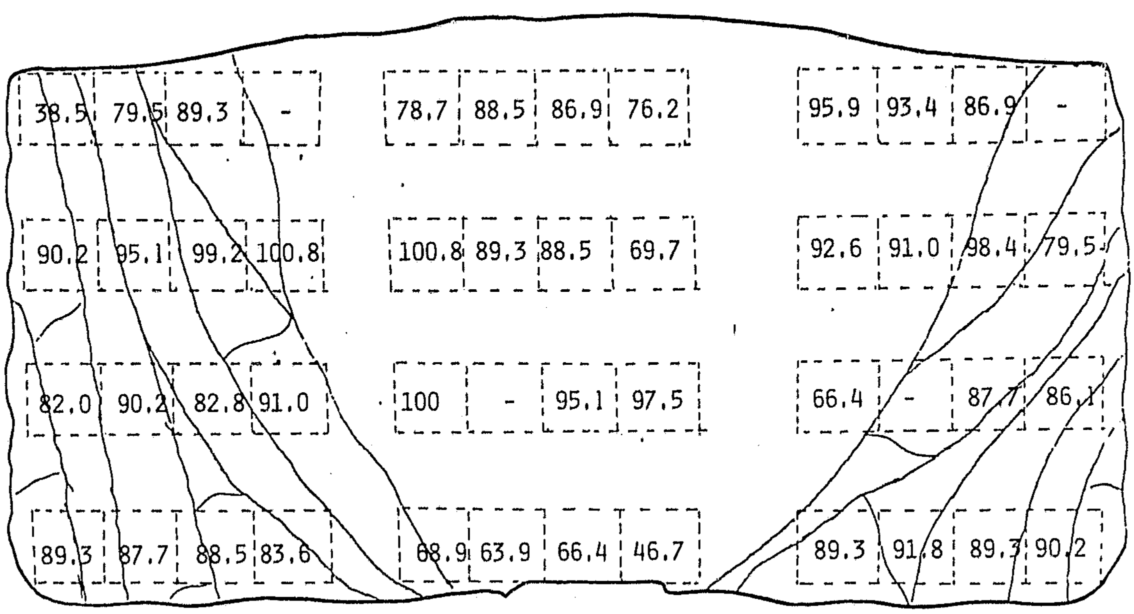
HEM I.D. 41-41C



AVERAGE η FOR THE WHOLE CRYSTAL: 10.7% AM1

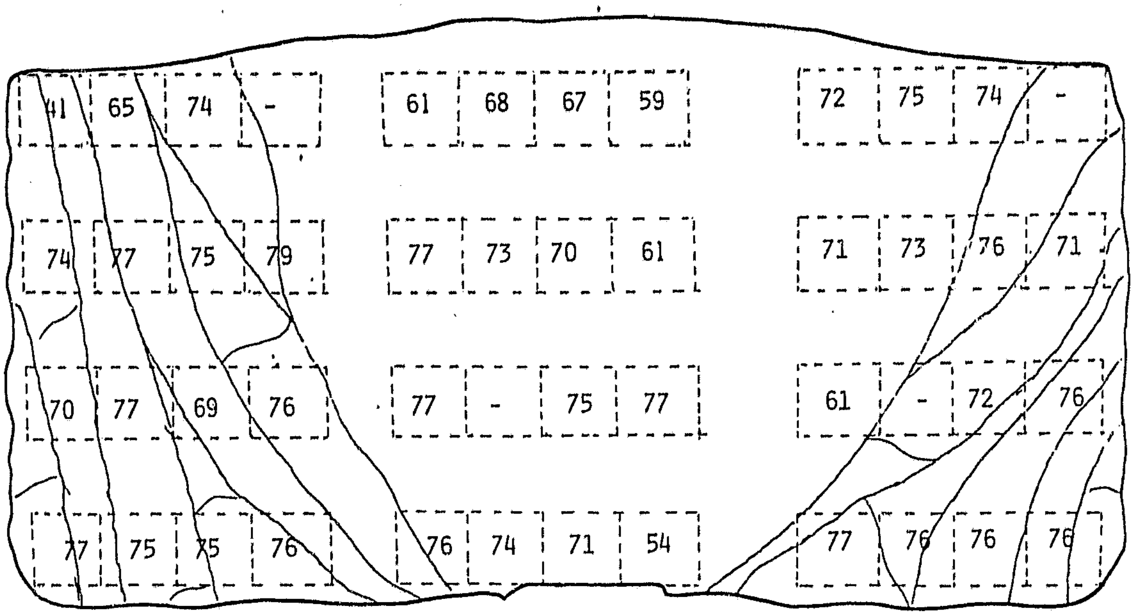
NORMALIZED TO Cz CONTROL: 87%

Map of Normalized η (% to Control) for Center Layer of Vertically Cut HEM (41-41C)



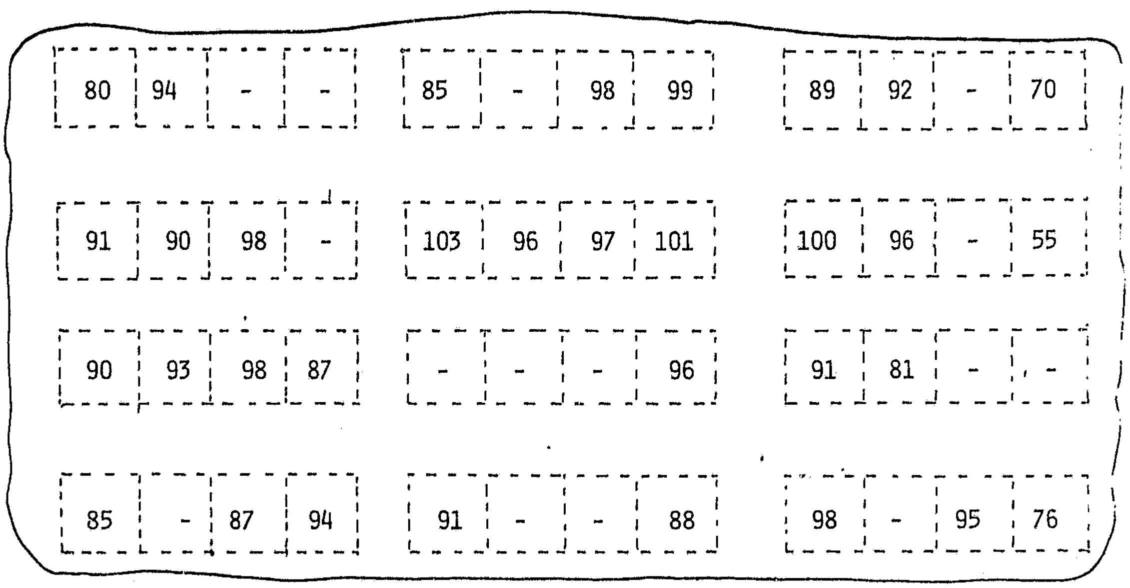
AVE. 85.1%

Map of CFF (%) For Center Layer of Vertically Cut HEM (41-41C)



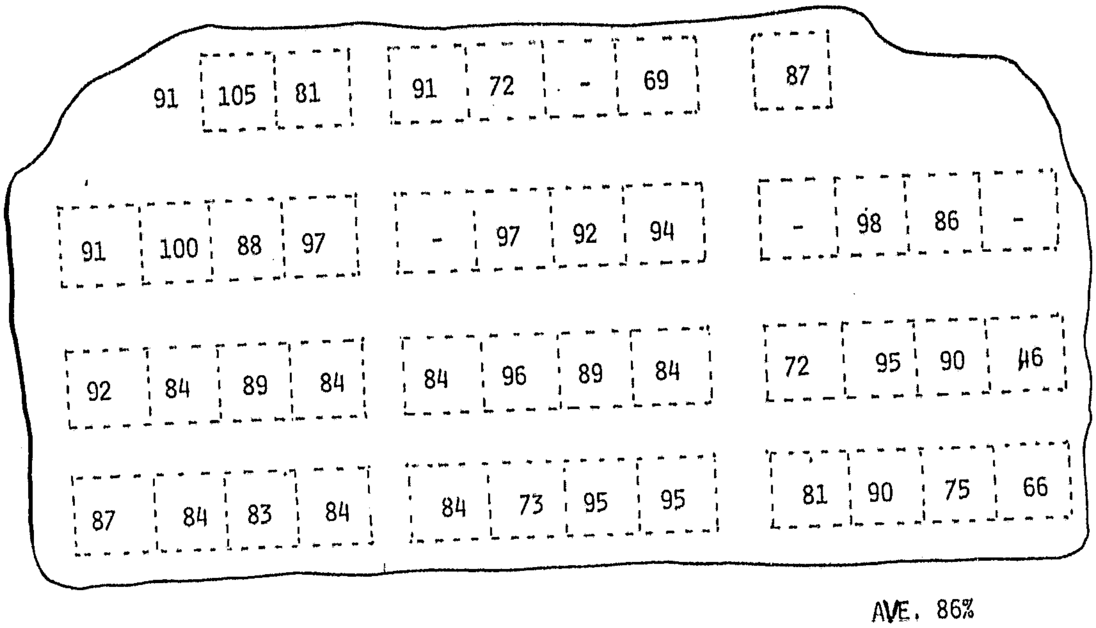
AVE.: 72% (93%)
CONTROL AVE.: 76%

Map of Normalized η (% to Control) for Quarter Layer of Vertically Cut HEM (41-41C)

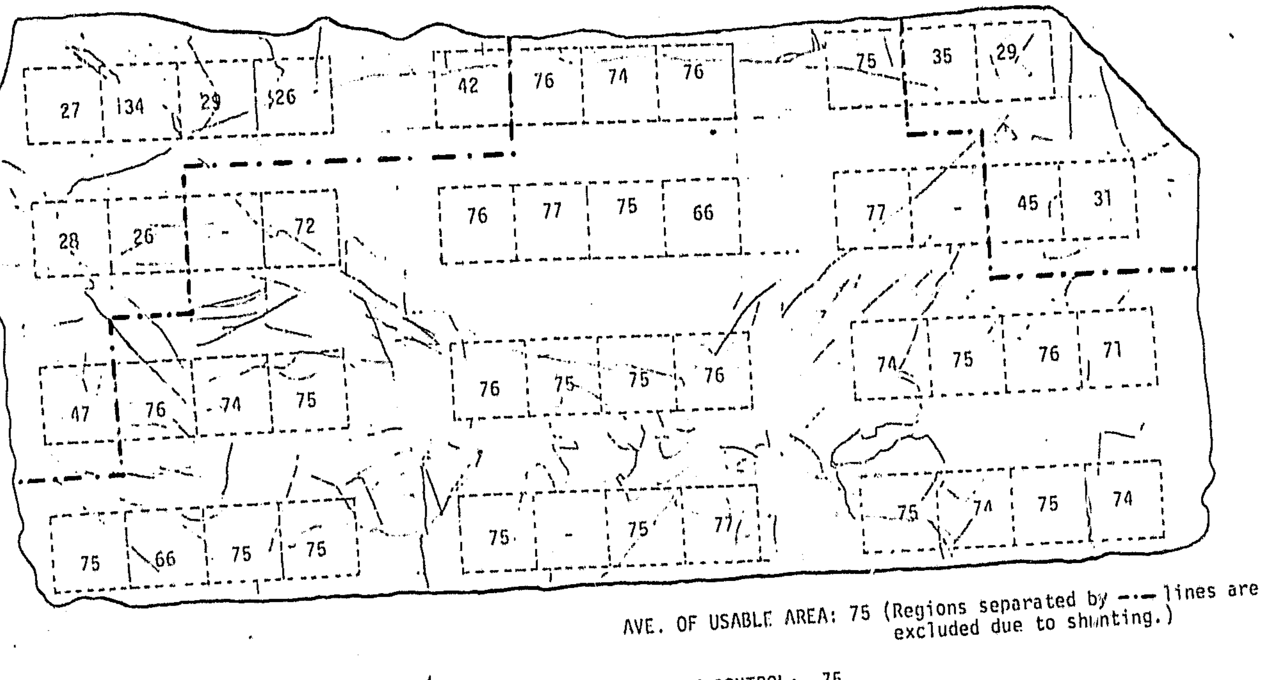


AVE. 90%

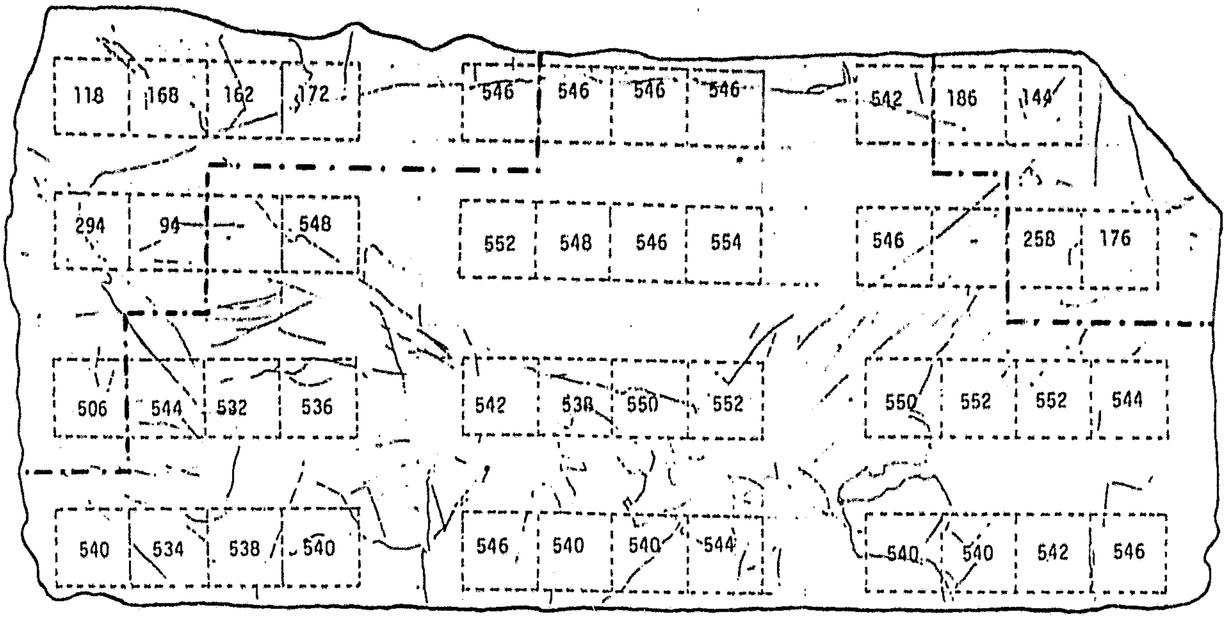
Map of Normalized η (% to Control) for Edge Layer of Vertically Cut HEM (41-41C)



Map of CFF (%) for Quarter Layer of Vertically Cut HEM (41-48)



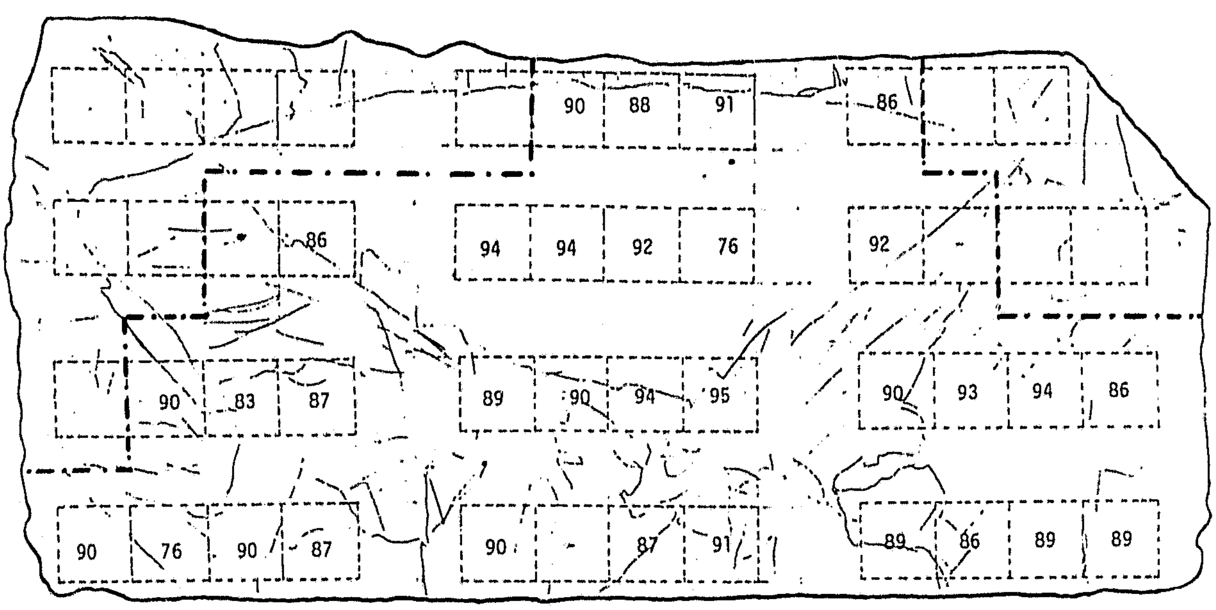
Map of V_{OC} (mV) for Quarter Layer of Vertically Cut HEM (41-48)



AVE. OF USABLE AREA: 528 (Regions separated by —·— lines are excluded due to shunting)

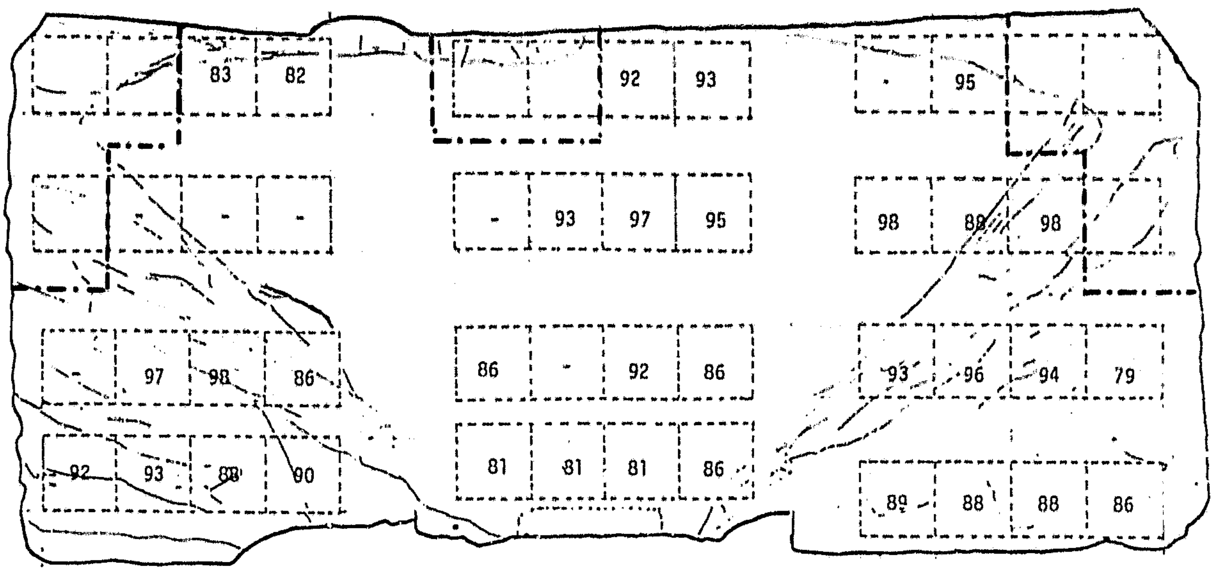
AVE. OF CONTROL: 578

Map of Normalized η (% to Control) for Quarter Layer of Vertically Cut HEM (41-48)



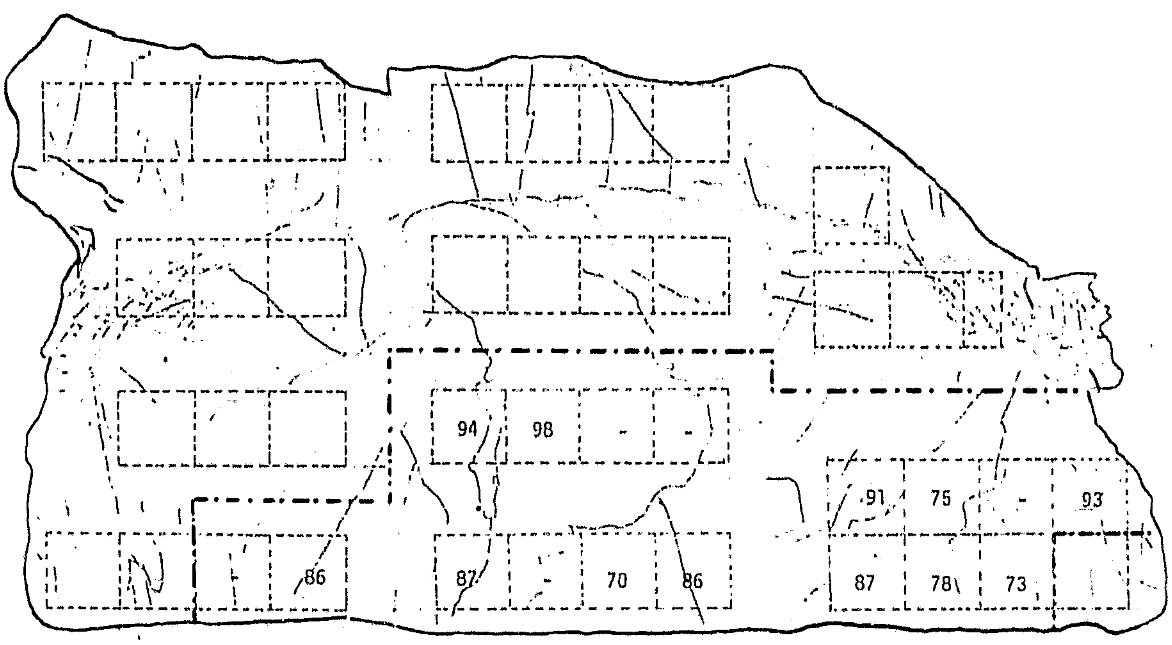
AVE. OF USABLE AREA: 89% (Regions separated by —·— lines are excluded due to shunting.)

Map of Normalized η (% to Control) for Center Layer of Vertically Cut HEM (41-48)



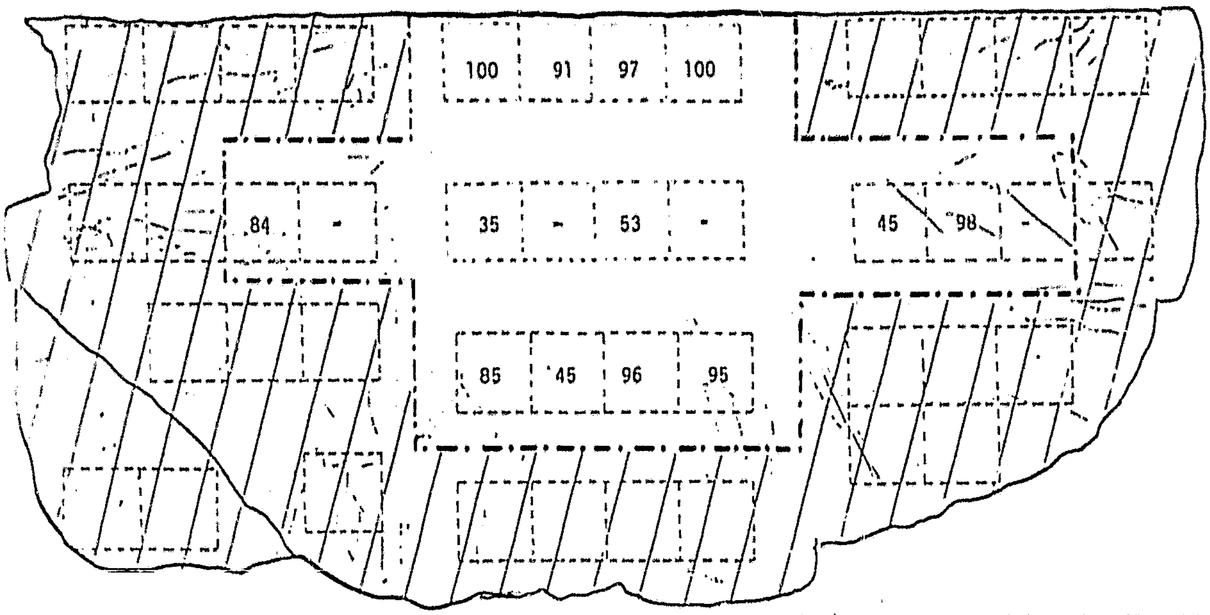
AVE. OF USABLE AREA: 90 (Regions separated by —·— lines are excluded due to shunting.)

Map of Normalized η (% to Control) for Edge Layer of Vertically Cut HEM (41-48)



AVE. OF USABLE AREA: 84% (Regions seaprated by —·— lines are excluded due to shunting. In this case, the whole upper region is excluded.)

Map of Normalized η (% to Control) of Top Layer of Horizontally Cut HEM (41-48)

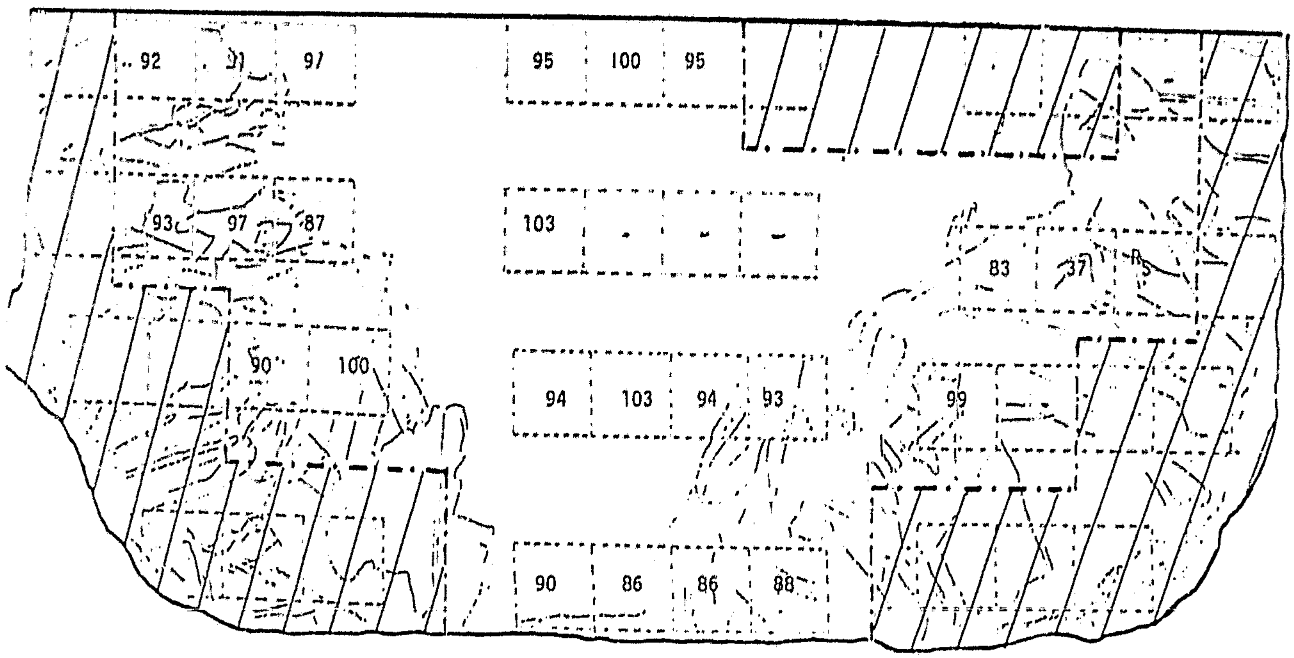


AVE. OF USABLE AREA: 79% (SHADED AREAS ///ARE EXCLUDED DUE TO SHUNTI

ESTIMATED PERCENTAGE OF USABLE AREA: 39%

ESTIMATED TOTAL EFFICIENCY VS. CONTROL: .79 x .39 = 31%

Map of Normalized η (% to Control) of Middle Layer of Horizontally Cut HEM (41-48)



AVE. OF USABLE AREA: 91% (SHADED AREA ARE EXCLUDED DUE TO SHUNTING)
ESTIMATED PERCENTAGE OF USABLE (i.e. NON-SHADED) AREA: 67%
TOTAL EFFICIENCY VS. CONTROL: .91 x .67% = 61%

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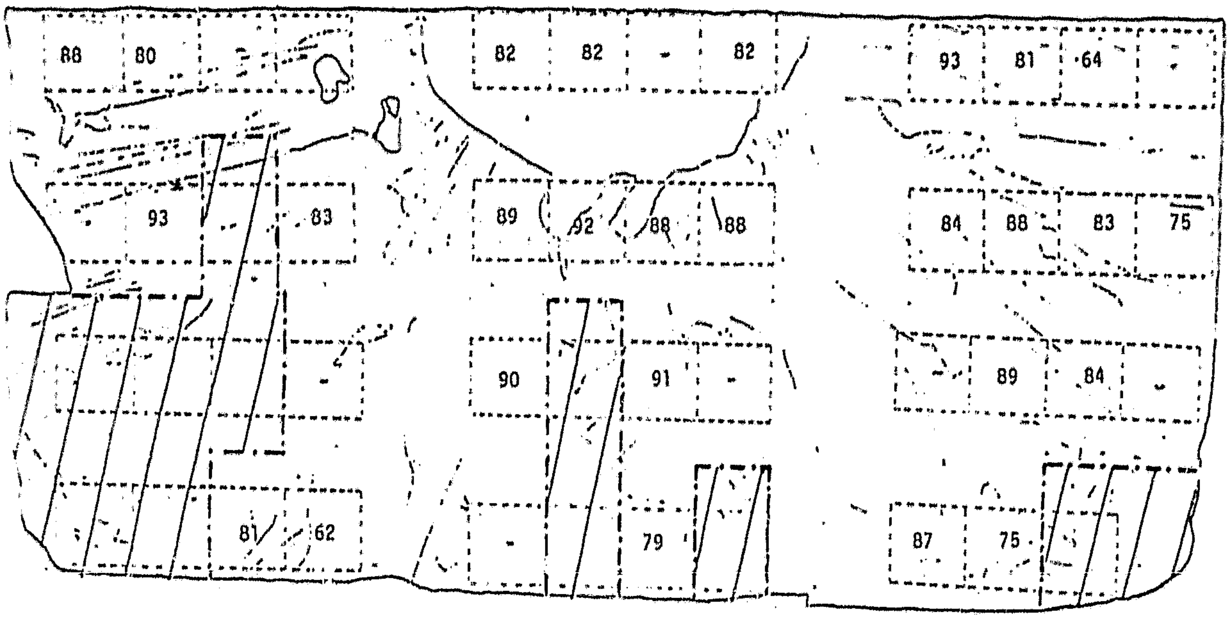
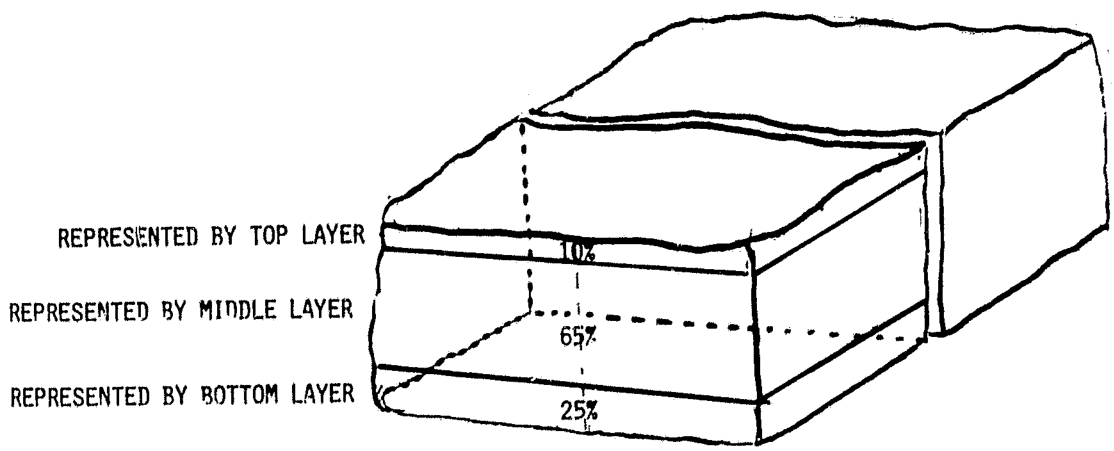
Map of Normalized η (% to Control) of Bottom Layer of Horizontally Cut HEM (41-48)



AVE. OF USABLE AREA: 83% (SHADED AREA///ARE EXCLUDED DUE TO SHUNTING)
ESTIMATED PERCENTAGE OF USABLE (i.e. NONSHADED) AREA: 89%
ESTIMATED TOTAL EFFICIENCY VS. CONTROL: .83 x .89 = 74%

HEM I.C. 41-48



EFFECTIVENESS OF THE TOTAL CRYSTAL NORMALIZED TO CZ CONTROL:61%

Analysis of Westinghouse Samples

JPL SAMPLE #	NO. OF DISLOCATIONS PITS/FIELD	NO. OF DISLOCATIONS PITS/um^2
J250-4.7-A	17.808	2.737×10^{-4}
J250-4.7-B	14.946	2.298×10^{-4}
J250-4.7-C	12.146	1.867×10^{-4}
J250-4.7-D	16.614	2.554×10^{-4}
J250-4.7-E	15.526	2.387×10^{-4}
J250-4.7-F	15.800	2.429×10^{-4}
J250-4.7-K_1	15.828	2.433×10^{-4}
J250-4.7-K_2	16.615	2.554×10^{-4}
J250-4.7-L_1	37.424	5.753×10^{-4}
J250-4.7-L_2	27.082	3.702×10^{-4}

Summary of Pre-Characterized Web Wafers

	Voc (mV)	Jsc (mA/cm^2)	CFF (%)	(%)
AVERAGE	534	26.3	77	10.8
STANDARD DEVIATION	1	.1	1	.2
RANGE	532-534	26.2-26.5	76-78	10.6-10.8

Minority Diffusion Lengths of Pre-Characterized Web Cells

SAMPLE I.D.	L_D(um)
C	65
T2	62
F	58
K-1	62
K-2	63
L	62
Control #11	121

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TECHNOLOGY DEVELOPMENT AREA

Encapsulation Task

C. D. Coulbert, Chairman

MATERIAL DURABILITY AND LIFE ASSESSMENT

Developing quantitative relationships that relate environmental stress such as solar ultraviolet, wind, temperature extremes, and moisture to the rate of degradation of module performance and structural integrity are objectives of the Encapsulation Task in-house efforts. These activities are integrated with contractual activities to develop an overall module-life-prediction method.

Photothermal degradation rates and mechanisms and ultraviolet absorption characteristics of polymeric encapsulants are being measured as a function of polymer composition and test-exposure conditions. Data are being obtained for silicones, EVA, PnBA, polyurethane, EMA, PVB, and acrylic films. Failure mechanisms and critical temperature limits associated with module hot-cell experience are being identified for use in establishing module circuit design and diode protection criteria.

Encapsulation material degradation data for cost-competitive advanced encapsulant systems is being gathered using various test hardware such as minimodules (12 x 16 in.), two-cell modules and individual material samples. Exposure facilities include the JPL laboratory test chamber and selected California field test sites at Point Vicente, JPL, Goldstone, and Table Mountain.

Solar-cell corrosion protection provided by various encapsulants, coatings and primers is being studied by Rockwell Science Center using a galvanic-cell atmospheric corrosion monitor (ACM). Initial results confirm that metallic surfaces encapsulated with properly bonded polymers will not corrode even in the presence of strong acidic or alkaline liquids in contact with the surface of the protective polymer. Further studies will assess the effects of contaminated interfaces and polymer encapsulants that have been photothermally degraded.

ENCAPSULATION ENGINEERING

New material products tailored to the specific requirements defined and publicized by the LSA Project for PV module encapsulation are now available from Du Pont and 3M for the PV manufacturers. These products include non-blocking EVA film in production quantities, laminated EVA-Tedlar sheets, and PMMA UV-screening cover films.

A display of these and other candidate polymeric encapsulation materials was presented in the 18th PIM exhibit area. These materials, provided at the request of the Encapsulant Task, were assembled to demonstrate the status, source, availability and form of candidate module encapsulants for pottants, cover films, edge seals and gaskets, adhesives and primers.

A JPL report titled Photovoltaic Module Encapsulation Design and Materials Selection, JPL Document No. 5101-177, has been written and is in

press; it describes the module encapsulant material requirements for the various functional elements of a complete photovoltaic module encapsulation package. This information is presented in terms of material properties, performance, life and cost requirements. It describes the status and availability of potential material and process candidates with criteria and guidelines for their selection, processing, and optimizing configurations for specific applications. A preliminary draft volume of this report was available in the PIM exhibit area and its publication and distribution is expected in about three months.

Under a contract with the University of Massachusetts to develop polymerizable UV stabilizers, the synthesis of 2(2-hydroxy-5-isopropenylphenyl) 2H-benzotriazole (2H5P) and its copolymerization has been accomplished. The compound does not homopolymerize and grafting with 2H5P has not been successful. At the same time, and based on the same intermediates as those used for the synthesis of 2H5P, a new synthesis of 2(2hydroxy-5-vinylphenyl) 2H-benzotriazole (2H5V) has been carried out that promises to have advantages over that accomplished earlier.

Grafting of 2H5V onto a number of common polymers has been accomplished, including atactic polypropylene, poly-[ethylene-co-vinyl (acetate)], poly-(methyl methacrylate), poly-(butyl acrylate) and polycarbonate. In preliminary experiments 2H5B does not graft under similar conditions.

Efforts will continue to evaluate the spectral characteristics of these compounds in attempts to establish clearly and beyond any doubt the most effective polymerizable derivative of 2(2-hydroxyphenyl) 2H-benzotriazole as the prime candidate for polymerizable UV stabilizers for the Low-Cost Solar Array Project.

Progress was reported on the Illinois Tool Works contract to develop and demonstrate the capability to produce operational solar cells having front and back metallizations and antireflective coatings deposited by gasless ion plating. In summary, it is noteworthy that the process has repeatedly produced cells that perform as well as or better than comparable commercial cells at a projected (SAMIS) production cost of 5.6¢/W_p for the metallization plus AR coating.

Spectrolab, Inc., reported progress in the experimental verification of their module-design analysis methods, evaluating the effects of various module encapsulant-design parameters on module thermal response, optical performance, electrical isolation, and solar-cell stresses. A summary of the tests on optical performance and electrical isolation is included in its presentation, below. One significant result of the electrical tests was that module electrical isolation approaching intrinsic material properties could be achieved with two or more dielectric layers (pottant plus film). All break-downs, however, occurred finally at sharp corners and edges of solar cell or circuit components. Voids and bubbles in the encapsulant did not significantly contribute to electrical breakdown.

A joint effort with Spectrolab is under way to develop graphical design analysis curves, i.e., master curves with reduced variables. These curves, when defined and verified, will enable the module designer to optimize the encapsulant system design parameters such as pottant thickness, pottant modulus,

and cover-film properties and to determine which module performance characteristics are most affected by encapsulant configuration and material choices.

Progress in the development and characterization of other advanced encapsulant materials by Springborn Laboratories, Inc., JPL, and the interested industrial groups was summarized by E. F. Cuddihy of JPL and P. Willis of Springborn. A summary of property and performance data is included below.

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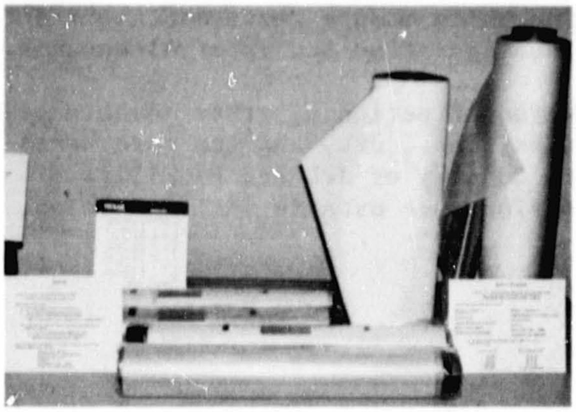
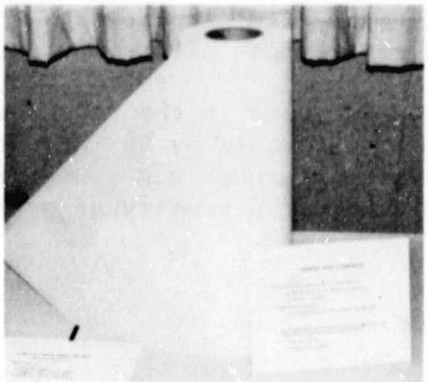
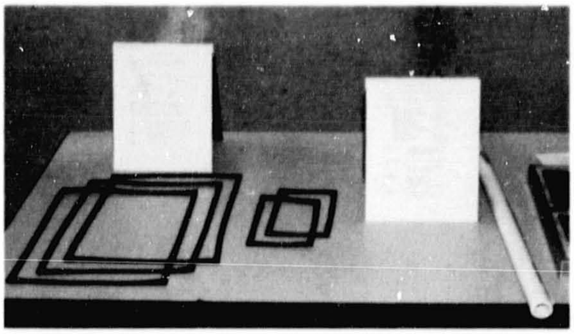
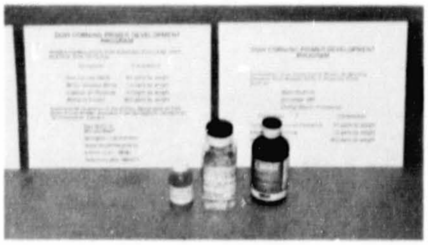
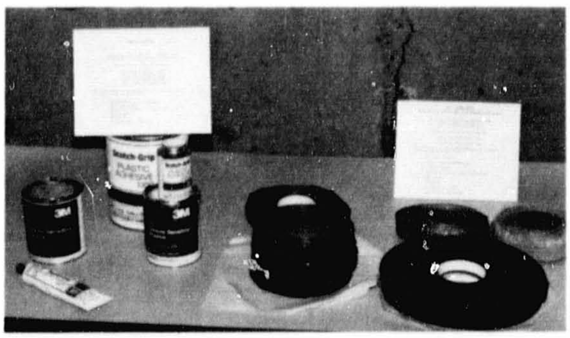
BLACK AND WHITE PHOTOGRAPH

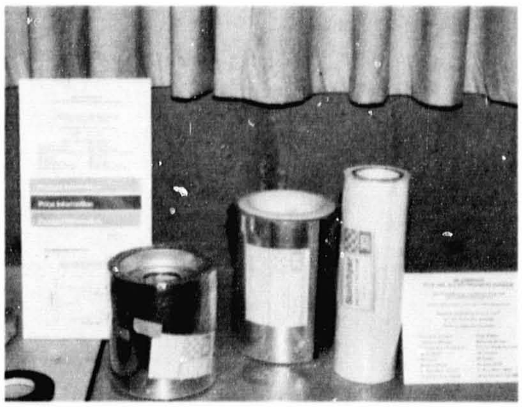












MINIMODULE PROGRAM

ADVANCED MODULE TESTING

JET PROPULSION LABORATORY

Minimodule Qualification Test Results

S/N CE 112, 114, 115 — GLASS / EVA / CELLS / CRANEGLASS / EVA / MYLAR

PRETEST: PMAX = 10.81 WATTS

TEMP TEST: PMAX = 10.60 WATTS (-1.9%)
GAS POCKETS MOVED TO THE BACKS OF CELLS (2 MODULES)

HUMIDITY/FREEZE TEST: PMAX = 10.64 WATTS (-1.5%)
TACKY SEALANT (3 MODULES)
DELAMINATION (1 MODULE)

S/N DE 111, 112, 113 — KORAD / EVA / CELLS / CRANEGLASS / WHITE EVA / SUPERDORLUX / CRANEGLASS / WHITE EVA

PRETEST: PMAX = 6.45 WATTS

TEMP TEST: PMAX = 4.86 WATTS (-24.7%)
CRACKED CELL (2 MODULES)
EDGE DISCOLORATION (1 MODULE)
DELAMINATION (1 MODULE)
WRINKLED FILM (1 MODULE)

HUMIDITY/FREEZE TEST: PMAX = 2.61 WATTS (-59.5%)
DISTORTED INTERCONNECTS (3 MODULES)
SPLITS IN SURFACE FILM (2 MODULES)
ENCAPSULANT DISCOLORATION (1 MODULE)

ENCAPSULATION TASK

S/N DE 127, 128, 129 — GLASS / EVA / CELLS / WHITE EVA / CRANEGLASS / AL FOIL

PRETEST: PMAX = 6.21 WATTS

TEMP TEST: PMAX = 5.94 WATTS (-4.3%)
AL FOIL WRINKLED (3 MODULES)
ENCAPSULANT DISCOLORATION (1 MODULE)
CRACKED CELL (1 MODULE)

HUMIDITY/FREEZE TEST: PMAX = 5.84 WATTS (-5%)
ENCAPSULANT EDGE DISCOLORATION (2 MODULES)
EDGE SEALANT FLOW (2 MODULES)
DISTORTED INTERCONNECTS (1 MODULE)

S/N CE 128, 129, 130 — GLASS / EVA / CELLS / CRANEGLASS / EVA / ACMETITE

PRETEST: PMAX = 10.80 WATTS

TEMP TEST: PMAX = 10.60 WATTS (-1.9%)
GAS POCKETS MOVED UNDER CELLS (3 MODULES)
AL FOIL WRINKLED (3 MODULES)

HUMIDITY/FREEZE TEST: 10.64 WATTS (-1.5%)
TACKY SEALANT (2 MODULES)
ENCAPSULANT DISCOLORATION AT EDGES (2 MODULES)
GAS POCKETS (1 MODULE)

ENCAPSULATION TASK

S/N DE 141, 142, 143

KORAD / EVA / CELLS / CRANEGLASS / WHITE EVA / GAL. STEEL / CRANEGLASS / WHITE EVA

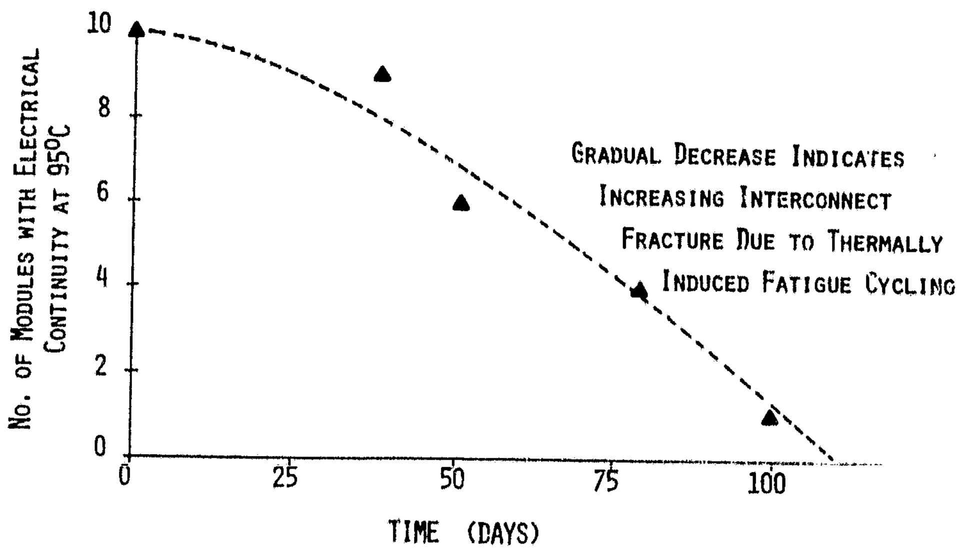
PRETEST:	PMAX = 6.50 WATTS
TEMP TEST:	PMAX = 6.23 WATTS (-4.2%) WRINKLED FILM (3 MODULES) ENCAPSULANT EDGE DISCOLORATION (1 MODULE) DELAMINATION (1 MODULE)
HUMIDITY/FREEZE TEST:	PMAX = 6.13 WATTS (-5.7%) EDGE SEALANT FLOW (3 MODULES) SURFACE FILM SPLITTING (3 MODULES)

Minimodule Qualification Tests

Serial No.	Pmax, Watts: Original	Pmax, Watts: After Temp Test	Pmax, Watts: After Humidity/Freeze Test	Comments: After Temp Test	Comments: After Humidity/Freeze Test
CE-112	11.24	11.08 (-1.4%)	11.19 (-0.4%)	No Change.	Sealant tacky.
CE-114	10.51	10.28 (-2.2)	10.23 (-2.7)	Gas pockets moved to backs of cells.	Sealant tacky, delamination.
CE-115	10.68	10.45 (-2.2)	10.50 (-1.7)	" " " " " " "	" "
CE-128	10.83	10.65 (-1.7)	10.69 (-1.3)	Gas pockets moved under cells, Al foil wrinkled.	Sealant tacky, Encapsulant discoloration
CE-129	10.88	10.65 (-2.1)	10.65 (-2.1)	Gas pockets moved under cells, Al foil wrinkled.	Gas pockets.
CE-130	10.69	10.50 (-1.8)	10.58 (-1.0)	Gas pockets moved under cells, Al foil wrinkled.	Sealant tacky, Encapsulant discoloration at edges.
DE-111	6.24	6.09 (-2.4)	5.88 (-5.8)	Cracked cell, film wrinkled, edge discoloration.	Encapsulant discoloration, interconnects distorted.
DE-112	6.81	2.54 (-62.7)	1.83 (-73.1)	Cracked cell.	Interconnect distorted, splits in surface film.
DE-113	6.29	5.95 (-5.4)	0.12 (-98.1)	Delamination.	Interconnect distorted, splits in surface film.
DE-127	6.05	5.82 (-3.8)	5.59 (-7.6)	Al foil wrinkled.	Encapsulant discolored at edges, Interconnect distorted.
DE-128	6.24	5.96 (-4.5)	5.96 (-4.5)	Al foil wrinkled, Encapsulant discoloration.	Edge sealant flow.
DE-129	6.34	6.05 (-4.6)	5.98 (-5.7)	Al foil wrinkled, Cracked cell.	Edge sealant flow, Encapsulant discoloration at edges.
DE-141	6.71	6.48 (-3.4)	6.35 (-5.4)	Delamination, wrinkled, film encapsulant discoloration at edges	Edge sealant flow, splits in surface film.
DE-142	6.50	6.09 (-7.6)	5.98 (-8.0)	Wrinkled film.	Edge sealant flow splits in surface film.
DE-143	6.28	6.12 (-2.5)	6.05 (-3.7)	" "	Edge sealant flow splits in surface film.

Battelle Accelerated Test Results

ELECTRICAL CONTINUITY AT 95°C



INDUSTRIAL ACTIVITIES

JET PROPULSION LABORATORY

E. F. Cuddihy

Industrial Contacts

- AMERICAN CYANAMID
- AMERICAN PLYWOOD ASSOCIATION
- CIBA-GEIGY
- CORNING GLASS
- CRANE COMPANY
- CYRO INDUSTRIES
- DEVELOPMENT ASSOCIATES, INC.
- DOW CORNING
- DUPONT
- GENERAL ELECTRIC
- GRACE (EMERSON AND CUMING, INC.)
- GULF OIL CHEMICALS
- HEXCEL
- ICI AMERICAS, INC.
- MASONITE
- MEAD PAPERBOARD PRODUCTS
- MONSANTO
- NATIONAL STARCH AND CHEMICAL CORP
- OWENS-CORNING FIBERGLAS
- PAWLING RUBBER COMPANY
- POTLATCH
- QUINN INDUSTRIES
- RICHARDSON COMPANY
- ROHM AND HAAS
- ROWLAND, INCORPORATED
- SHELDAHL
- SHELL DEVELOPMENT CO.
- SPAULDING FIBER COMPANY
- 3M COMPANY
- UNION CARBIDE
- U.S. GYPSUM
- XCEL

DuPont–Rowland Ethylene Vinyl Acetate (EVA) Laminating Film

A) COST (QUOTED APRIL, 1981)

QUANTITY, ft^2	PRICE RANGE, ¢/ft^2
> 25,000	31 TO 33
> 50,000	30 TO 32
> 100,000	25 TO 27
> 250,000	23 TO 25
> 500,000	TO BE NEGOTIATED

B) TECHNICAL SALES AND INFORMATION

WILLIAM J. WALKER
JOSEPH TICE
ROWLAND, INCORPORATED
SPRUCE BROOK INDUSTRIAL PARK
BERLIN, CONN. 06037

TELEPHONE (203) 828-6364

ROBERT WASHBURN
DUPONT
ETHYLENE POLYMERS DIVISION
PLASTIC PRODUCTS AND RESINS DEPT.
CHESTNUT RUN
WILMINGTON, DEL. 19898

TELEPHONE (302) 999-3057

Dupont Tedlar Products

A) COMMERCIAL

1) CLEAR, UV SCREENING TEDLAR FILMS FOR FRONT COVER APPLICATIONS

2) WHITE-PIGMENTED TEDLAR FILMS FOR BACK COVER APPLICATIONS

B) EXPERIMENTAL

1) WHITE-PIGMENTED AND CLEAR, UV SCREENING TEDLAR FILMS SURFACE COATED WITH AN ADHESIVE FOR BONDING TO EVA (ADHESIVE DESIGNATION 68040)

2) BACK COVER LAMINATE CONSISTING OF WHITE TEDLAR/68040/EVA

C) TECHNICAL SALES AND INFORMATION

JOSEPH D.C. WILSON II
DUPONT
POLYMER PRODUCTS DEPARTMENT
CHESTNUT RUN-FILM
WILMINGTON, DEL. 19898

TELEPHONE (302) 999-3253

3M Co. Film and Allied Products Division

A) CLEAR, UV SCREENING ACRYLIC FILMS FOR FRONT COVER APPLICATIONS (X-22416, X-22417)

B) WHITE-PIGMENTED "SCOTCHPAR" POLYESTER FILMS FOR BACK COVER APPLICATIONS (SCOTCHPAR-20-CP-WHITE)

C) TECHNICAL SALES AND INFORMATION

RICHARD G. LUNDGREN
3M COMPANY
3M CENTER
BUILDING 236-GA
ST. PAUL, MINN. 55101

TELEPHONE (612) 733-4281

ROGER BREKKEN
3M COMPANY
3M CENTER
BUILDING 223-55
ST. PAUL, MINN. 55101

TELEPHONE (612) 733-1969

3M Co. Adhesives, Coatings and Sealers Division

A) "WEATHERBAN" FAMILY OF BUTYL EDGE SEALING TAPES

B) PRESSURE-SENSITIVE ADHESIVE SOLUTIONS

C) COATINGS FOR WOOD AND STEEL

D) TECHNICAL SALES AND INFORMATION

MICHAEL JONES
3M COMPANY
3M CENTER
BUILDING 223-6N-02
ST. PAUL, MINN. 55101

TELEPHONE (612) 733-7198

More Materials

A) AVAILABLE FOR PV INDUSTRY EVALUATION

1) ETHYLENE METHYL ACRYLATE (EMA) LAMINATING FILM
2) POLY-n-BUTYL ACRYLATE (P-n-BA) CASTING LIQUID
3) ALIPHATIC POLYETHER URETHANE CASTING LIQUIDS
4) EPDM EDGE GASKETS

B) UNDER INVESTIGATION

1) ANTI-SOILING COATINGS (i.e., L-1168, 3M COMPANY)
2) POLYMERIC AND MONOMERIC UV STABILIZERS (AMERICAN CYANAMID)
3) HIGH PERFORMANCE ANTI-OXIDANTS (AMERICAN CYANAMID)
4) LIQUID ACRYLIC CASTING RESINS

PRIMER DEVELOPMENT BY E. P. PLUEDDEMAN OF DOW CORNING CORP.

JET PROPULSION LABORATORY

E. F. Cuddihy

Primer Formulation for EVA–Glass

A) PRIMER FOR BONDING EVA TO GLASS

B) PRIMER FOR BONDING EVA TO POLYESTER FILMS SUCH AS MYLAR, SCOTCHPAR, LLUMAR

C) PRIMERS FOR EMA, P-n-BA, URETHANES

Primer Formulation for EVA–Glass

COMPONENT	COMPOSITION
DOW CORNING Z-6030	90 PARTS BY WEIGHT
BENZY DIMETHYL AMINE	10 PARTS BY WEIGHT
LUPERSOL 101 PEROXIDE	1 PART BY WEIGHT

USE OPTIONS

A. "SELF-PRIMING" EVA – DISPERSE THE THREE COMPONENT MIXTURE INTO EVA PELLETS PRIOR TO FILM EXTRUSION (QUANTITY, 1 wt.% IN EVA FILM)

B. SEPARATE PRIMING OF SURFACES – DILUTE THE THREE COMPONENT MIXTURE IN METHANOL TO 10 wt.%, WIPE THINLY ONTO SURFACES AND ALLOW TO AIR DRY AT LEAST 15 minutes.

NOTES:

1. ADEQUACY OF BONDING EVA POTTANT TO FLUOROCARBON FILMS (e.g., TEDLAR) WITH THIS PRIMER SYSTEM NOT YET DEMONSTRATED

2. DILUTED PRIMER MIXTURE IN METHANOL AVAILABLE FROM SPRINGBORN UNDER THE DESIGNATION "A-11861-1, EVA PRIMER"

Primer Formulation for EVA–Polyester Films

COMPONENT	COMPOSITION
CYMEL 303 (AMERICAN CYANAMID)	90 PARTS BY WEIGHT
Z-6040 (DOW CORNING)	10 PARTS BY WEIGHT
METHANOL SOLVENT	300 PARTS BY WEIGHT

PROPERTIES OF ETHYLENE VINYL ACETATE (EVA)

JET PROPULSION LABORATORY

E. F. Cuddihy

Cured EVA (A-9918)

GLASS TRANSITION TEMPERATURE: -43°C

DENSITY: 0.92 gms/cc AT 25°C

THERMAL EXPANSION COEFFICIENT

a) BELOW Tg (-43°C) $0.9 \cdot 10^{-4}\ {}^{o}C^{-1}$

b) -43 TO +10°C $2.0 \cdot 10^{-4}\ {}^{o}C^{-1}$

c) ABOVE +10°C $4.0 \cdot 10^{-4}\ {}^{o}C^{-1}$

YOUNG'S MODULUS AT 25°C: 900 psi

TENSILE STRENGTH (25°C): 1900 psi

ELONGATION AT BREAK (25°C): 510%

THERMAL CONDUCTIVITY: $9 \cdot 10^{2}\ \frac{\text{watts-mil}}{\text{ft}^2 - {}^{o}C}$

SPECIFIC HEAT: $2.09\ \frac{\text{watts-sec}}{\text{gm}\ {}^{o}C}$

DIELECTRIC STRENGTH: 620 volts/mil

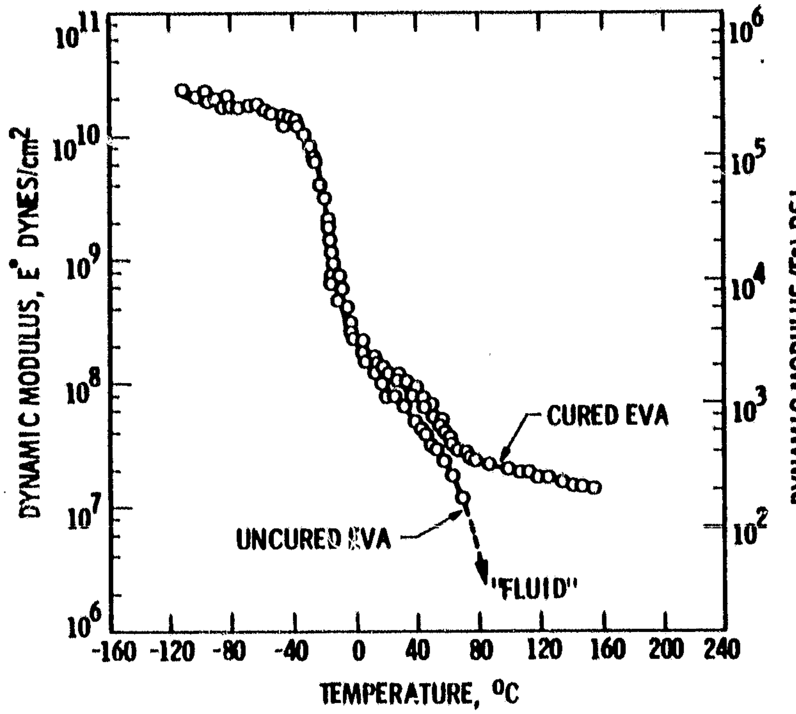
IR EMISSIVITY (25°C): 0.88 (CLEAR) 0.91 (WHITE)

REFRACTIVE INDEX: 1.482

OPTICAL TRANSMISSION: ≈ 92% (400 TO 800 mm)

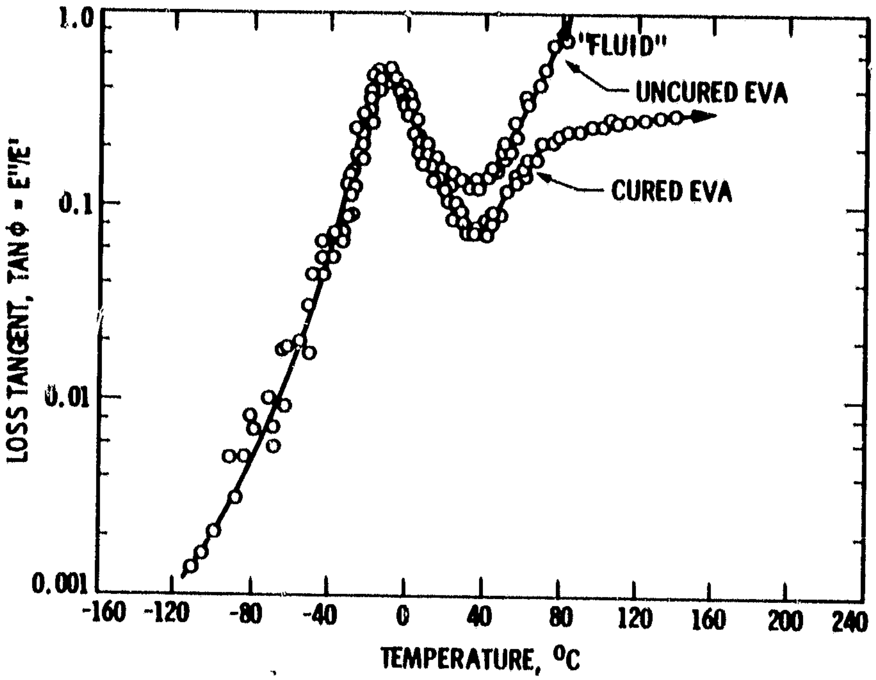
Dynamic Mechanical Properties

Dynamic Modulus (E*) of Encapsulation–Grade EVA (A-9918) at a Frequency of 110 Hz



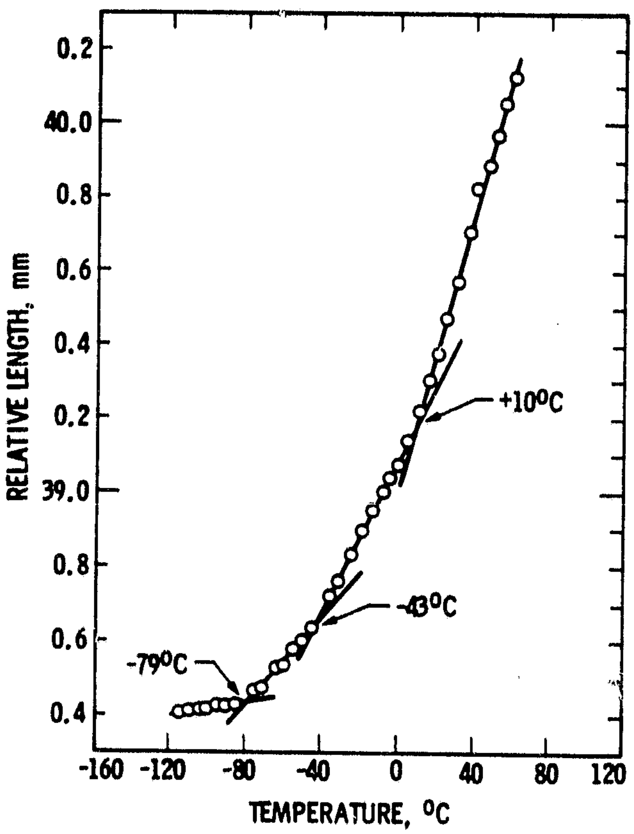
Dynamic Mechanical Properties

Loss Tangent (Tan ϕ) of Encapsulation–Grade EVA (A-9918) at a Frequency of 110 Hz



Cured EVA (Formulation A-9918)

Linear Expansion During Measurement of Dynamic Mechanical Properties at 110 Hz



Densities at 25°C of Encapsulation–Grade EVA (A-9918)

MATERIAL	DENSITY, gms/cc
ELVAX 150*	0.957
COMPOUNDED AND UNCURED EVA	0.97
COMPOUNDED AND CURED EVA	0.92

*FROM DUPONT TECHNICAL LITERATURE FOR ELVAX RESINS

General Speculations on Elvax EVA Resins

- ALL OF THEM BLOCK COPOLYMERS
- ALL HAVE 70/30 (VA/E) RANDOM COPOLYMER BLOCK
- ALL WOULD HAVE Tg $\approx$ - 43 TO - 44^{o}C
- DIFFERENCES AMONGST THE RESINS ARE PROBABLY
  1) WT. FRACTION DISTRIBUTION OF THE BLOCKS
  2) MOLECULAR WEIGHTS OF THE BLOCKS, ESPECIALLY PE BLOCK WHICH WOULD REGULATE MELTING POINT

Considerations for Improving Weatherability and Durability and Increasing Service Temperature of EVA

1) STABILIZATION OF POLYETHYLENE
2) STABILIZATION OF THE ETHYLENE/VINYL ACETATE BLOCK

ENCAPSULATION TASK

MASTER CURVES FOR STRUCTURAL ANALYSIS

JET PROPULSION LABORATORY

E. F. Cuddihy

Master Curve Development

General List of Structural Parameters Being Considered for Reduced–Variable Master–Curve Studies

POTTANTS –
1) MODULUS
2) THICKNESS
3) THERMAL EXPANSION COEFFICIENT
4) HYGROSCOPIC EXPANSION COEFFICIENT

SOLAR CELLS –
1) MODULUS
2) DIMENSIONS (THICKNESS, WIDTH, LENGTH)
3) THERMAL EXPANSION COEFFICIENT
4) INTERCELL SPACING
5) GEOMETRY (i.e., ROUND, SQUARE, RECTANGLE, ETC.)

PANELS –
1) MODULUS
2) DIMENSIONS (THICKNESS, WIDTH, LENGTH)
3) THERMAL EXPANSION COEFFICIENT
4) HYGROSCOPIC EXPANSION COEFFICIENT

Structural Analysis

Deflection and Thermal Stress

INPUT PROPERTIES

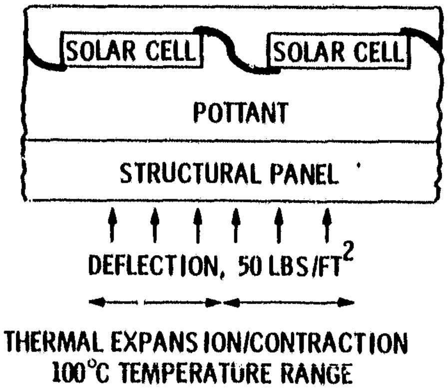
1) MODULUS
2) TENSILE STRENGTHS
3) THERMAL EXPANSION COEFF
4) PANEL THICKNESS
5) SOLAR CELL ALLOWABLE STRESSES
   a) DEFLECTION, 8000 PSI
   b) LINEAR (THERMAL), 5000 PSI

PRIMARY OUTPUT

GENERATED STRESS IN SOLAR CELLS AS A FUNCTION OF POTTANT THICKNESS BETWEEN CELLS AND STRUCTURAL PANEL

MODULE DESIGN FEATURES

1) 1.2 X 1.2 SQUARE METER
2) 10 X 10 SQUARE CM CELLS
3) 1.3 MM CELL SPACING



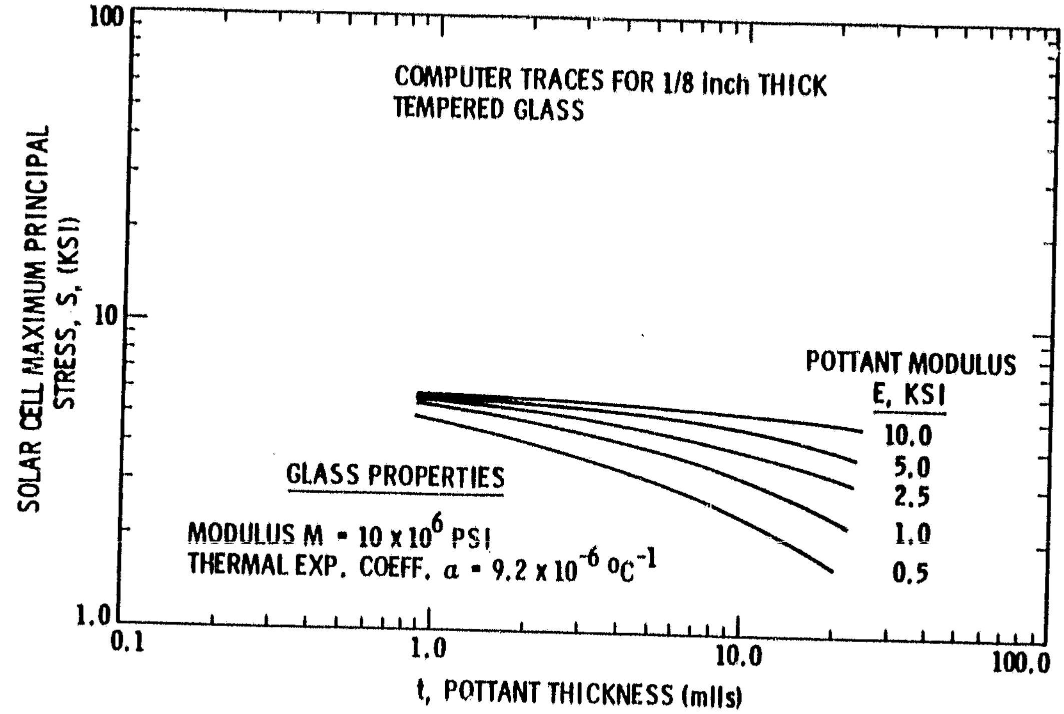
Structural Analysis

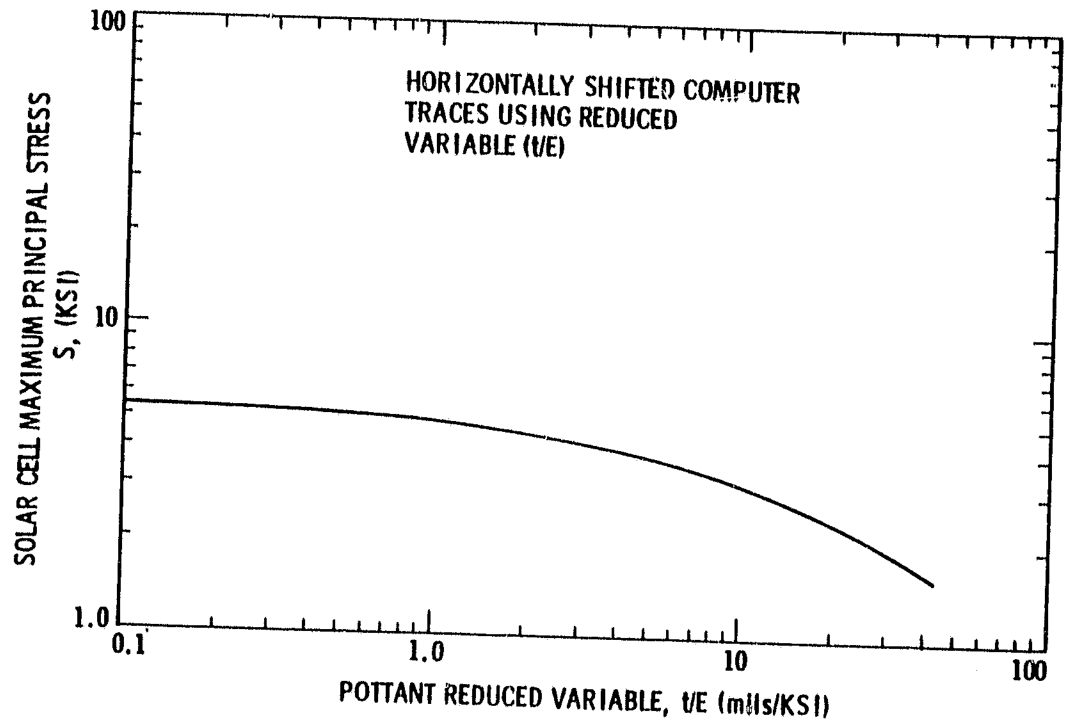
Structural Material Properties

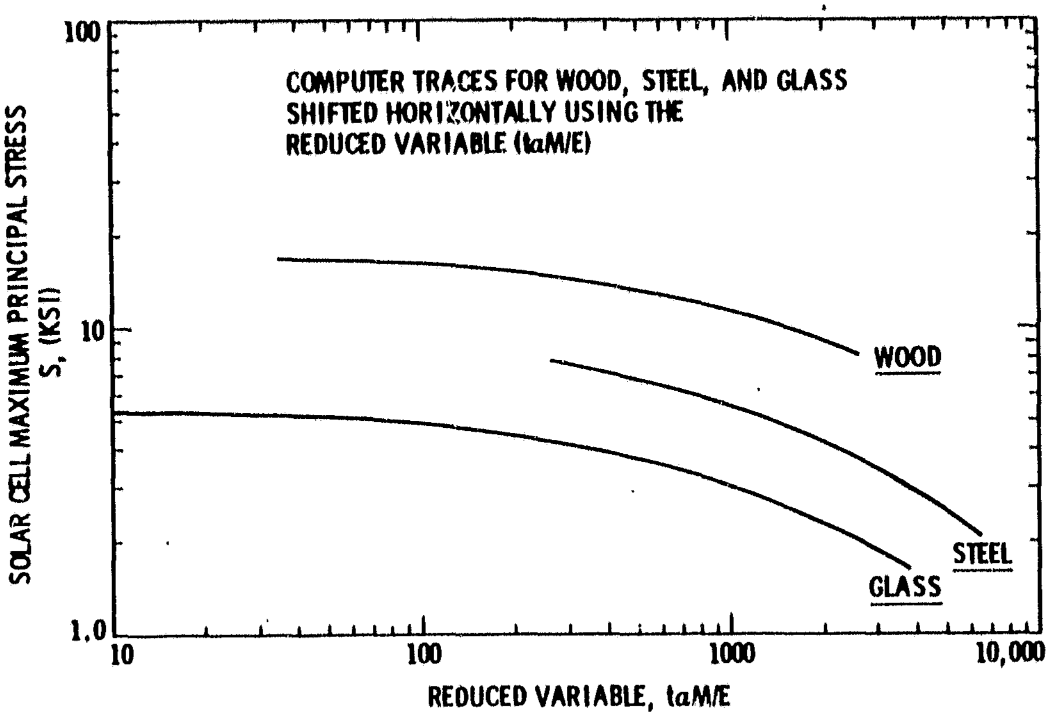
MATERIAL	MODULUS (PSI)	THERMAL EXP COEFFICIENT (IN/IN/°C)	ALLOWABLE STRESS (PSI)
GLASS			
TEMPERED	$10x10^6$	$9.2x10^{-6}$	13000
ANNEALED	$10x10^6$	$9.2x10^{-6}$	2000-3600
WOOD	$0.8\text{-}1.2x10^6$	$7.2x10^{-6}$	2500
SILICON	$17x10^6$	$4.4x10^{-6}$	5000-8000
STEEL	$30x10^6$	$10.8x10^{-6}$	28000

THERMAL STRESS ANALYSIS (ΔT = 100°C)

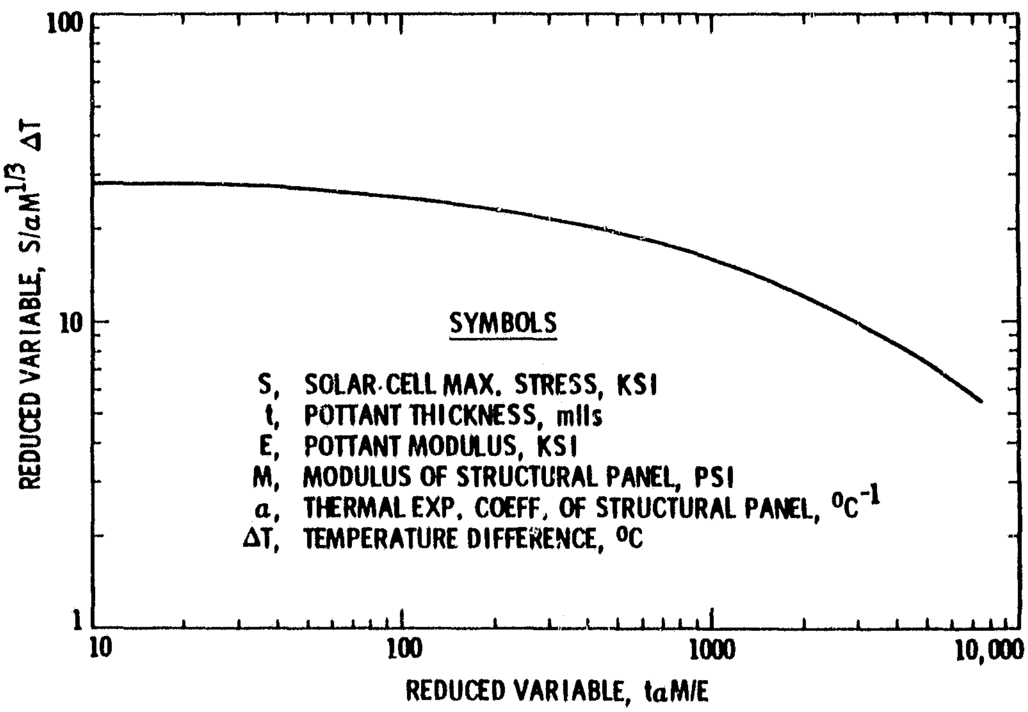
Glass Superstrate Design





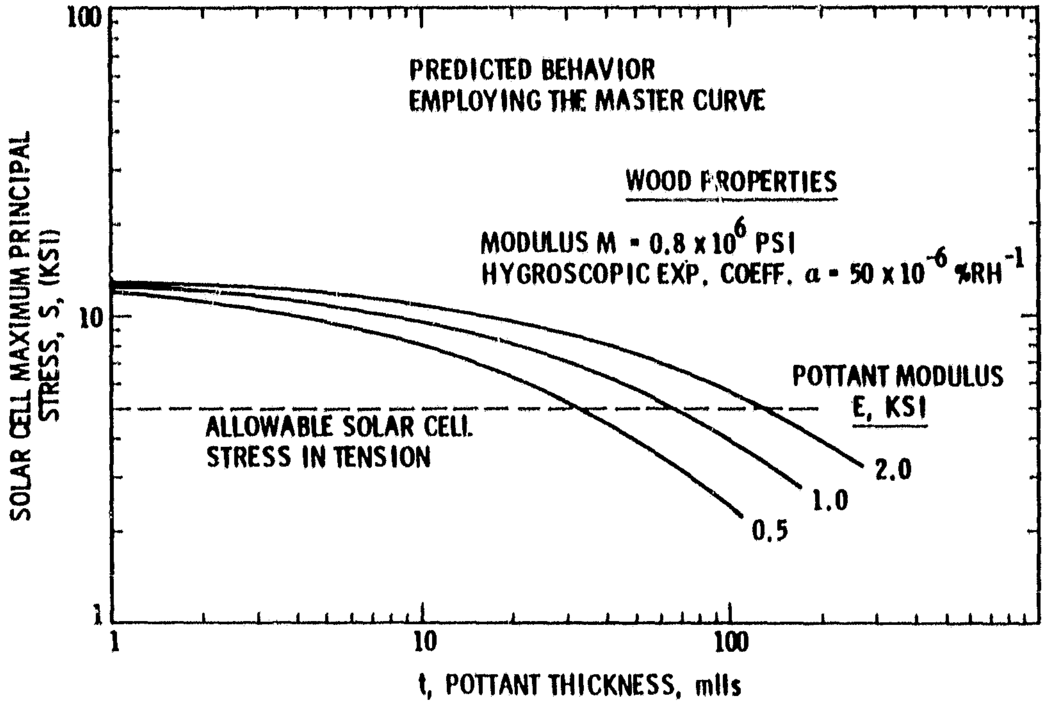


Master Curve for Thermal Stress Analysis



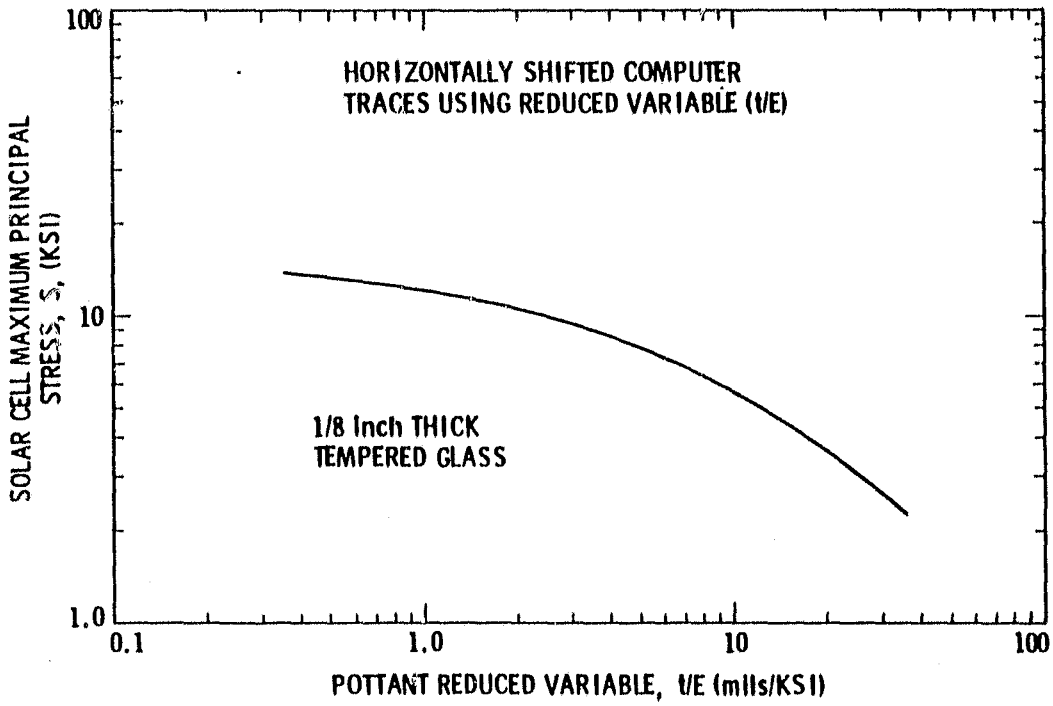
Hygroscopic Stress Analysis (ΔRH = 100%)

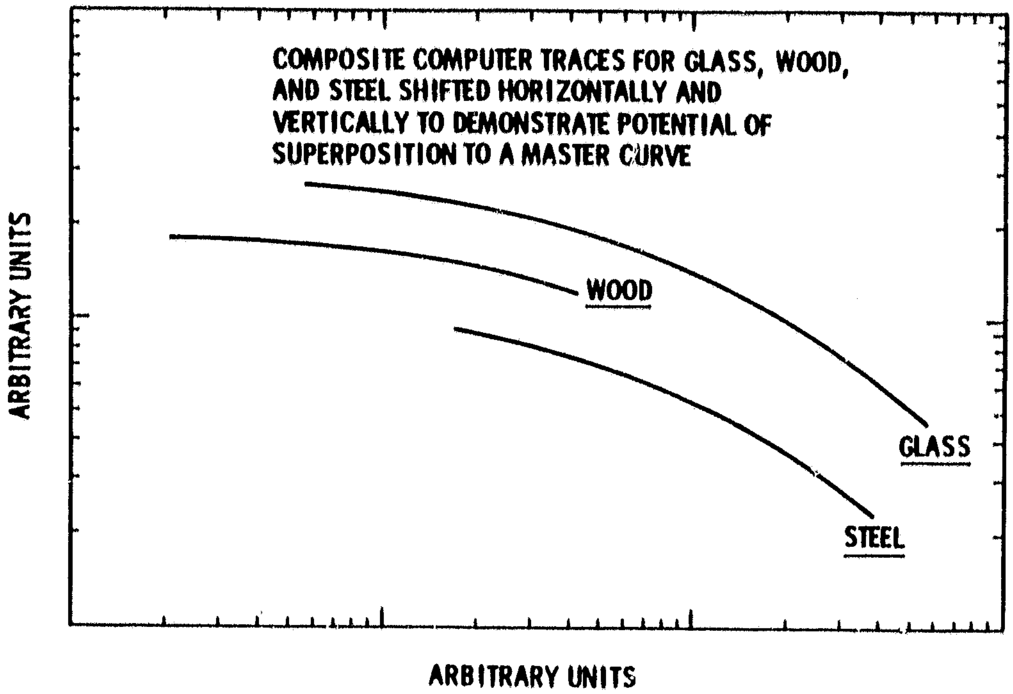
Wooden Substrate Design



Deflection Stress Analysis (Load = 50 lb/ft^2)

Glass Superstrate Design

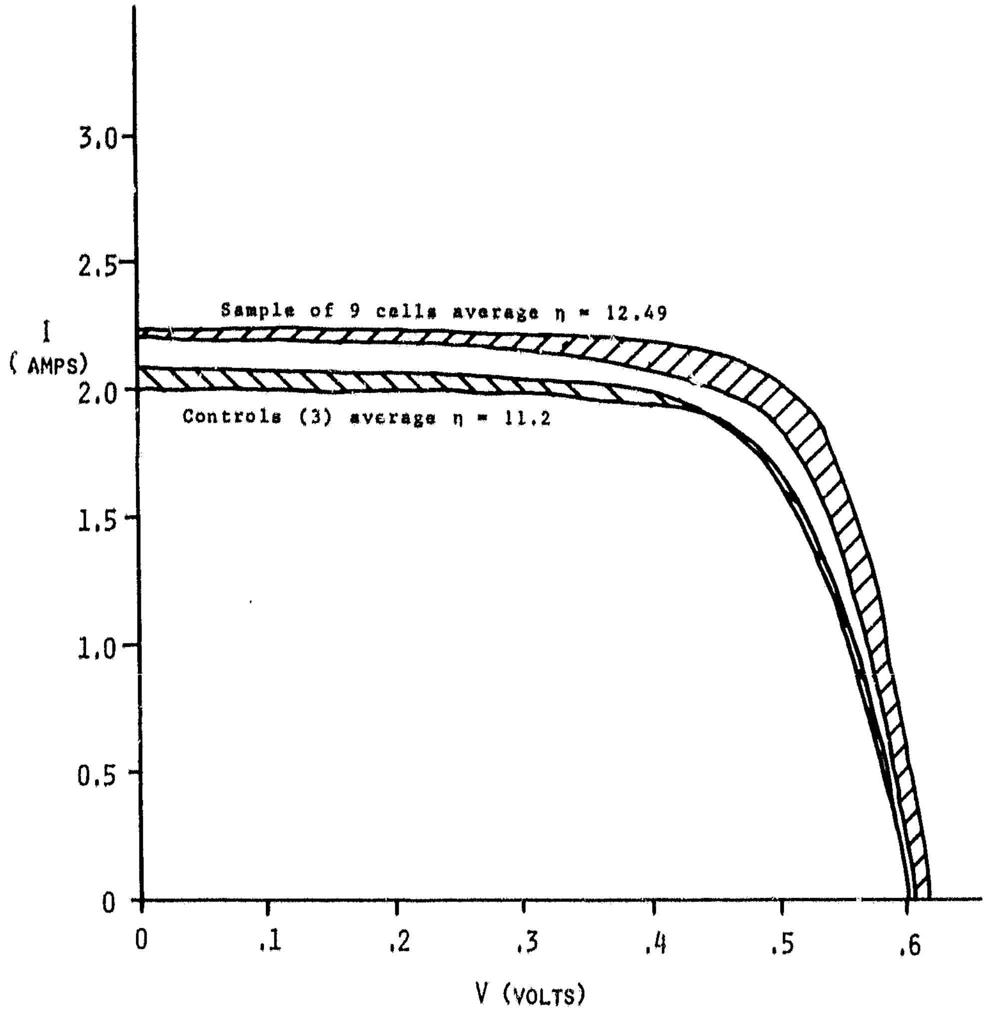




ION PLATING

ILLINOIS TOOL WORKS–ENDUREX

- -- DEVELOP ION PLATING FOR DEPOSITION OF METALLIZATION ON SOLAR CELLS.
- -- DEVELOP MASKING TECHNIQUES TO BEST MAKE USE OF ION PLATING DEPOSITED METALLIZATION.
- -- DEVELOP LOW COST METALLIZATION SYSTEMS FOR USE ON SOLAR CELLS.
- -- DEVELOP ION PLATING DEPOSITED AR COATINGS.



Ion Plating SAMIS Results

.056 ($1980)/PEAK-WATT

BASED ON:

- -- 50 MW/YEAR PRODUCTION
- -- 4" DIAMETER ROUND CELLS
  - -- NI/CU FRONT METALLIZATION
  - -- TI/CU BACK METALLIZATION
  - -- SiO_X AR
- -- 6 VACUUM SYSTEMS + 1 RECYCLE STATION

IPEG SENSITIVITY ANALYSIS IS IN PROCESS

Future Opportunities and Problems

A) METALLIZATION OF CELLS WITH OTHER THAN ROUND SHAPES.

-- SQUARE CELLS

-- RIBBON SILICON

B) JUNCTION FORMATION AND METALLIZATION IN SAME MACHINE.

-- ION IMPLANT JUNCTION

-- LASER RECRYSTALLIZATION

-- ION PLATE METALLIZATION AND AR

REQUIRES:

-- SEPARATE VACUUM SYSTEMS FOR IMPLANT AND ION PLATING OPERATIONS

-- MATCHED THROUGHPUTS

C) DEPOSITION OF JUNCTION AND METALLIZATION BY ION PLATING IN ONE MACHINE

-- DEPOSIT DOPED SI LAYER ~4000 Å THICK

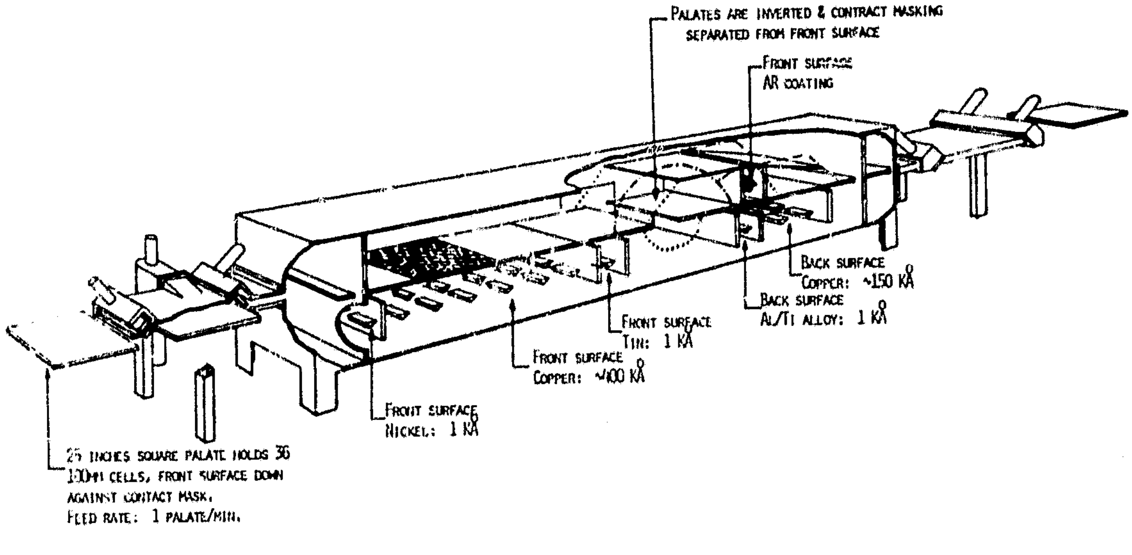
-- LASER RECRYSTALLIZATION

-- ION PLATE METALLIZATION AND AR

REQUIRES:

-- DEVELOPING RECRYSTALLIZATION TECHNIQUES

-- DETERMINING PROFILE OF RESULTING JUNCTION



ENCAPSULANT DESIGN ANALYSIS AND VERIFICATION

SPECTROLAB, INC.

Optical Verification Testing

- 13 SPECIMENS, TWO CELLS EACH
- XENON AND TUNGSTEN SIMULATORS (AM0 AND AM1)
- COMPARE BARE VERSUS ENCAPSULATED CELLS

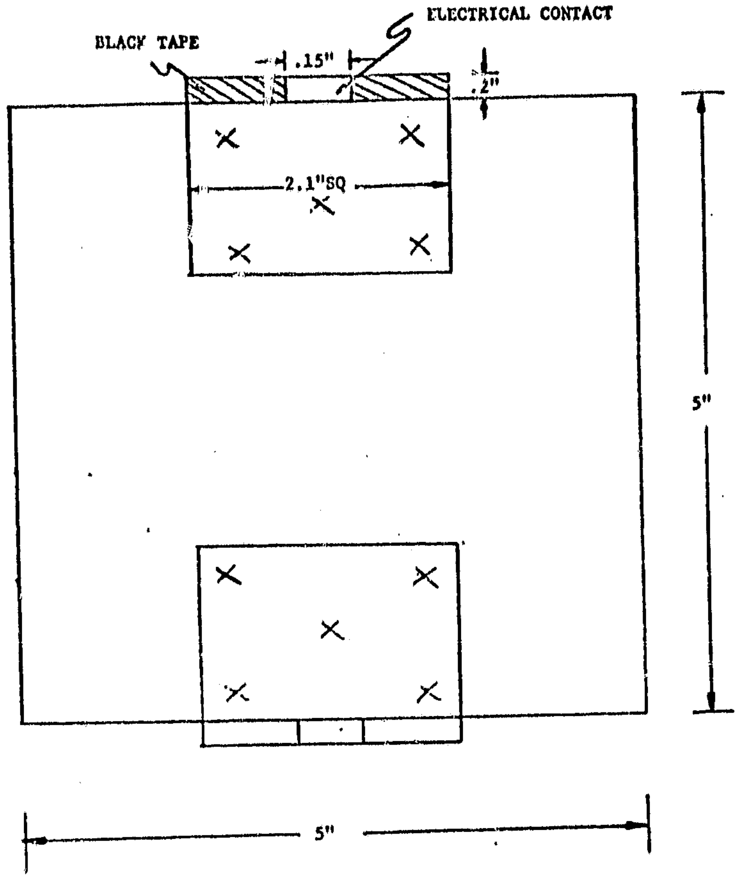
Optical Test Specimens

COUPON NO.	OC-1	OC-2	OC-3	OC-4	OC-5	OC-6	OC-7	OC-8	OC-9	OC-10	OC-11	OC-12	OC-13
Load Bearing Member	Low-Iron Glass Stipple-In	Low-Iron Glass Stipple-In	High-Iron Glass	Low-Iron Glass Stipple-In	Low Iron Glass Stipple-Out	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Top Cover	--	--	--	--	--	Korad	Tedlar	Tedlar	Tedlar	Tedlar	Tedlar	Tedlar	Tedlar
Encapsulant	EVA	EVA	EVA	EVA/CG	EVA/CG	EVA	EVA	EVA/CG	EVA/CG	EVA/CG	EVA	EVA	EVA/CG
Encapsulant Thickness	10 mil	10 mil	10 mil	10 mil	10 mil	10 mil	10 mil	10 mil	10 mil	10 mil	54 mil	10 mil	10-mil
Cell Type*	SC-2"Sq	PC-2"x4"	SC-2"Sq	SC-2"Sq	SC-2"Sq	SC-2"Sq	SC-2"Sq	SC-2"Sq	SC-2"Sq (AR)	SC-2"D (Text)	SC-2"Sq	SC-2"Sq (AR)	SC-2"D (AR-Text)
No. Cells	2	2	2	2	2	2	2	2	2	2	2	2	2

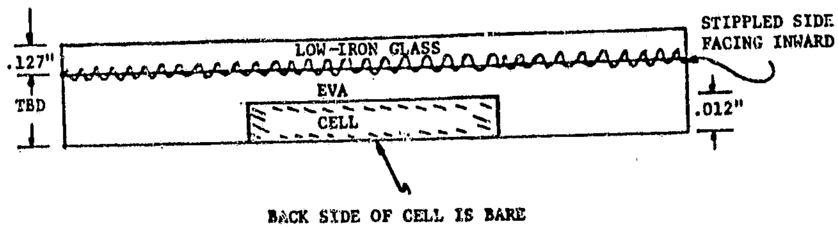
*SC - Single Crystal Silicon
PC - Polycrystalline Silicon

N/A - Not applicable for this test

Typical Optical Test Coupon



MEASURE TOTAL THICKNESS AT LOCATIONS MARKED "X"



Optical Results

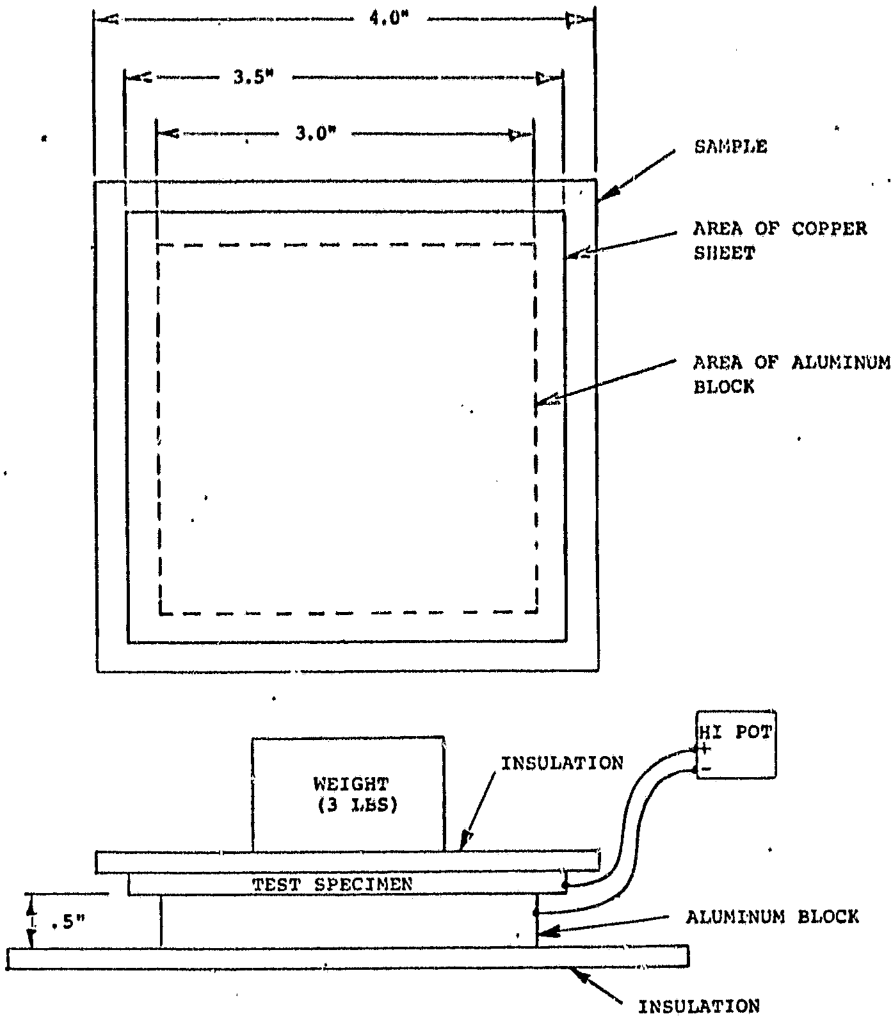
- STIPPLE IN VERSUS OUT NO EFFECT
- CRANE GLASS NO EFFECT
- EVA THICKNESS NO EFFECT
- IRON CONTENT LARGE EFFECT

Specimens for Electrical Verification Tests

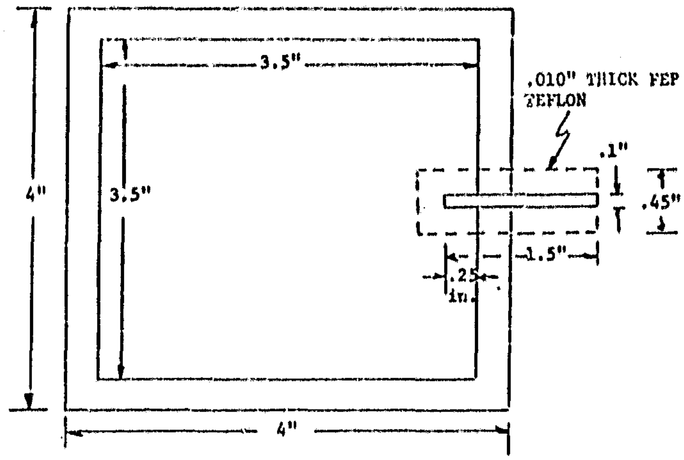
Type	Front Side		Back Side	
A	.004 Tedlar	.018" EVA/CG	.018" EVA/CG	.001 Al/Polyester
B	.001 Tedlar	.018" EVA/CG	.036" EVA/CG	.001 Al/Polyester
C	.001 Tedlar	.018" EVA	.018" EVA/CG	Wood*
D	.001 Tedlar	.036" EVA/CG	.036" EVA/CG	Wood*

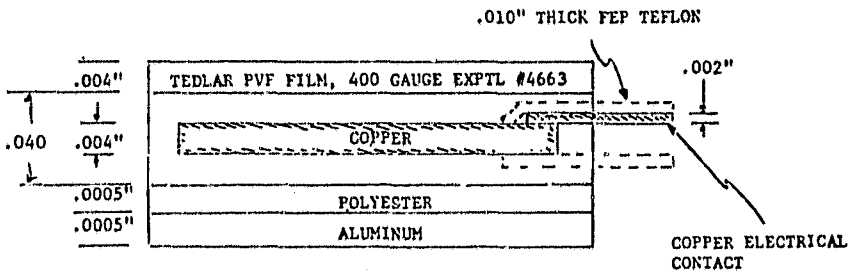
*Duron (U. S. Gypsum Co.)

Setup for Electrical Isolation Tests



Electrical Coupon, Type A





Summary of Electrical Test

Coupon	Type	Average Breakdown Voltage	Std. Dev.	High	Low
A	Front	15.6	2.8	19	12
B	Front	15.2	1.9	19	12
C	Front	13.2	3.6	21	5
D	Front w/C.G.	18.1	3.7	22	10
D	Front no C.G.	15.8	4.0	25	12
A	Back	6.8	3.1	11	1
B	Back	8.6	2.1	13	5
C	Back	22.2	4.2	25	8
D	Back	24.0	1.2	25	21

Electrical Results

- BREAKDOWN AT CORNERS AND EDGES
- VOIDS AND BUBBLES NOT SIGNIFICANT
- RELATIVELY HIGH DIELECTRIC STRENGTHS FOR ALL SAMPLES

Technology Voids in Electrical Test

- EFFECTS OF WEATHERING IGNORED
- MODEL DOES NOT TAKE FIELD CONCENTRATION EFFECTS INTO ACCOUNT
- EFFECTS OF CONTINUOUS ELECTRICAL FIELD NOT INVESTIGATED
- EDGE PROBLEMS IN FRAMING NOT INVESTIGATED

TOPICS IDENTIFIED REQUIRING FURTHER RESEARCH

Thermal–Structural

- EFFECT OF POTTANT SURROUNDING CELL COMPLETELY
- TEMPERATURE VARIATIONS OF STRUCTURAL PROPERTIES
- MATERIAL PROPERTIES OF POLYCRYSTALLINE VERSUS SINGLE CRYSTAL SILICON
- WEATHERING EFFECTS ON MATERIAL PROPERTIES
- RESIDUAL STRESS FROM ENCAPSULATION PROCESS

Structural–Deflection

- LOADING FROM BOTH SIDES OF MODULE
- COMPLETE ENCAPSULATION
- RESIDUAL STRESS
- STRESS MEASUREMENTS AT VARIOUS POINTS ON CELL
- STRESS AT INTERCONNECT POINTS
- VARYING MATERIAL PROPERTIES WITH TEMPERATURE
- CELL SHAPE AND SIZE/MODULE SIZE
- CELL THICKNESS
- WEATHERING EFFECTS

Thermal

- LOCATION OF MODULE IN ARRAY FIELD
- WIND PATTERNS IN ARRAY FIELD
- REFINEMENT OF CONVECTIVE HEAT TRANSFER ALGORITHM

Optical

- OFF NORMAL RADIATION
- ZERO DEPTH CONCENTRATOR EFFECTS
- DIFFUSE REFLECTION EFFECTS
- DIFFUSE SUNLIGHT EFFECTS

Electrical

- FIELD CONCENTRATION
- EFFECTS OF BUBBLES AND VOIDS
- EFFECTS OF MOISTURE
- EFFECTS OF ENCAPSULANT AGING

MATERIALS DEVELOPMENT

SPRINGBORN LABORATORIES, INC.

Status of Available Technology

ACCOMPLISHMENT	DATE
ETHYLENE VINYL ACETATE POTTANT	3/79
DEMONSTRATED DOUBLE VACUUM BAG LAMINATION TECHNIQUE FOR MODULE FABRICATION	6/79
NON-WOVEN GLASS SPACER IDENTIED	1/80
FORMULATION OF HIGH STRENGTH PRIMERS (GLASS/EVA)	9/80
GASKET MATERIAL/SUPPLIER IDENTIFIED	4/81
ETHYLENE/METHYL ACRYLATE POTTANT	5/81
POLYURETHANE CASTING SYRUP IDENTIFIED	6/81
BUTYL ACRYLATE POTTANT	7/81

Pottant Materials

- ETHYLENE VINYL ACETATE POTTANT
  A-9918
- DU PONT EXTRUSION OF EVA ON COMMERCIAL SCALE
- EXPLORING EVA/TEDLAR CO-EXTRUDED FILM
- SMALL VOLUME ORDERS (TO 30,000 FT^2)
  AVAILABLE - SPRINGBORN LABORATORIES
  CRANEGLASS INTERLEAF AVAILABLE

Ethylene Methyl Acrylate (EMA)

- COST, $0.59 / LB*
- HIGH THERMAL STABILITY
- ADHESION PROPERTIES (HOT MELT)
- NON-HYDROPHILIC
- ANTI-BLOCKING ADDITIVE AVAILABLE
- VACUUM BAG LAMINATION DEMONSTRATED
- INTEGRATED TRANSMISSION: 91.5%
- EXTRUDABLE IN THIN FILMS
- MELT INDEX, 6 GMS / 10 MINUTES

* GULF OIL CHEMICALS, BASE RESIN, TD - 938

EMA Formula No. A-13439

	PARTS
EMA TD 938 BASE RESIN	100.0
LUPERSON 101 (CURING AGENT)	3.0
CYASORB UV-531 (STABILIZER)	0.3
TINUVIN 770	0.1
NAUGARD - P (ANTIOXIDANT)	0.2

- INGREDIENTS TUMBLE BLENDED PRIOR TO EXTRUSTION - NO SEPARATE COMPOUNDING STEP REQUIRED
- NO RELEASE PAPER REQUIRED
- FOR USE IN VACUUM BAG LAMINATION

CURE STUDIES:

	DEGREE OF CURE, % GEL		
CURE TIME	130°C	140°C	150°C
10 MINUTES			0%
20 MINUTES			37%
30 MINUTES		LOW GEL	53%
40 MINUTES	LOW GEL	34%	63%
60 MINUTES	LOW GEL	47%	65%

THERMAL CREEP:

- BLOCKS OF CURED EMA AND UNCURED RESIN HUNG IN AIR OVEN AT 90° C - NO CREEP IN EITHER
- EMA HAS NO ESTABILISHED GEL REQUIREMENT, MAY NOT REQUIRE CURE.
- MODULES UNDER TEST AT 90° C

CURED PROPERTIES:

TENSILE STRENGTH, PSI	2,080
ULTIMATE ELONGATION, %	570
YOUNG'S MODULUS, PSI	3,200 *
INTEGRATED OPTICAL TRANSMISSION, %	90.5
HARDNESS, SHORE D	35
REFRACTIVE INDEX	1.49

* HAS A THICKNESS REQUIREMENT

- INDUSTRIAL EVALUATION SAMPLES AVAILABLE FROM SPRINGBORN LABORATORIES
- PILOT PLANT QUANTITIES AVAILABLE FROM SPRINGBORN AT $0.40 PER SQUARE FOOT
- STANDARD SIZE: 24 INCH WIDTH, 0.018 INCH THICK
- ROLLS OF APPX. 230 LINEAR FEET W/NO RELEASE INTERLEAF
- PRIMER: SPRINGBORN A11861 (TO GLASS)

Butyl Acrylate Casting Syrup BA 13870

(IDENTIFIED BY JPL)

CURRENT FORMULATION: BA 13870	PARTS
. BUTYL ACRYLATE POLYMER	35
. BUTYL ACRYLATE MONOMER	60
. HEXANEDIOLDIACRYLATE (CROSSLINKING AGENT)	5
. TINUVIN - P (UV SCREENER)	0.25
. TINUVIN 770 (UV STABILIZER)	0.05

SAMPLES ARE AVAILABLE FROM SPRINGBORN LABORATORIES FOR INDUSTRIAL EVALUATION

CURE CHARACTERISTICS:

- CURED IN 18 MINUTES AT 60° C, OR 14 MINUTES AT 70° C
- INITIATOR: ALPEROX - F , 0.5% BY WEIGHT (LAUROYL PEROXIDE)
- POT LIFE IN EXCESS OF 8 HOURS AT 25° C

Low–Temperature Initiators: Butyl Acrylate Pottant

INITIATOR	LEVEL	CURE TIME, (MINUTES)[A.]			
		25°C	35°C	45°C	60°C
LUPERSOL - 11	0.5	NP	NP	21	12
VAZO-33W	0.5	40	5.5	4	3
LUPERSOL - 11 STANNOUS OCTOATE	0.5 0.1	NP	29	11	5
ALPEROX -F (LAUROYL PEROXIDE)	0.5	NP	NP	NP	18

A. UNDER NITROGEN TO PREVENT INHIBITION

ALPEROX - F RECOMMENDED FOR INDUSTRIAL EVALUATION WORK :

- NON - GASSING
- NON - HAZARDOUS
- LONG POT LIFE, AT LEAST 8 HOURS
- RAPID CURE AT 60° C

Butyl Acrylate Syrup

PROPERTIES:

SYRUP: WATER WHITE, CLEAR
VISCOSITY APPX. 8,000 CENTIPOISE
SPECIFIC GRAVITY APPX. 0.94

CURED PROPERTIES:

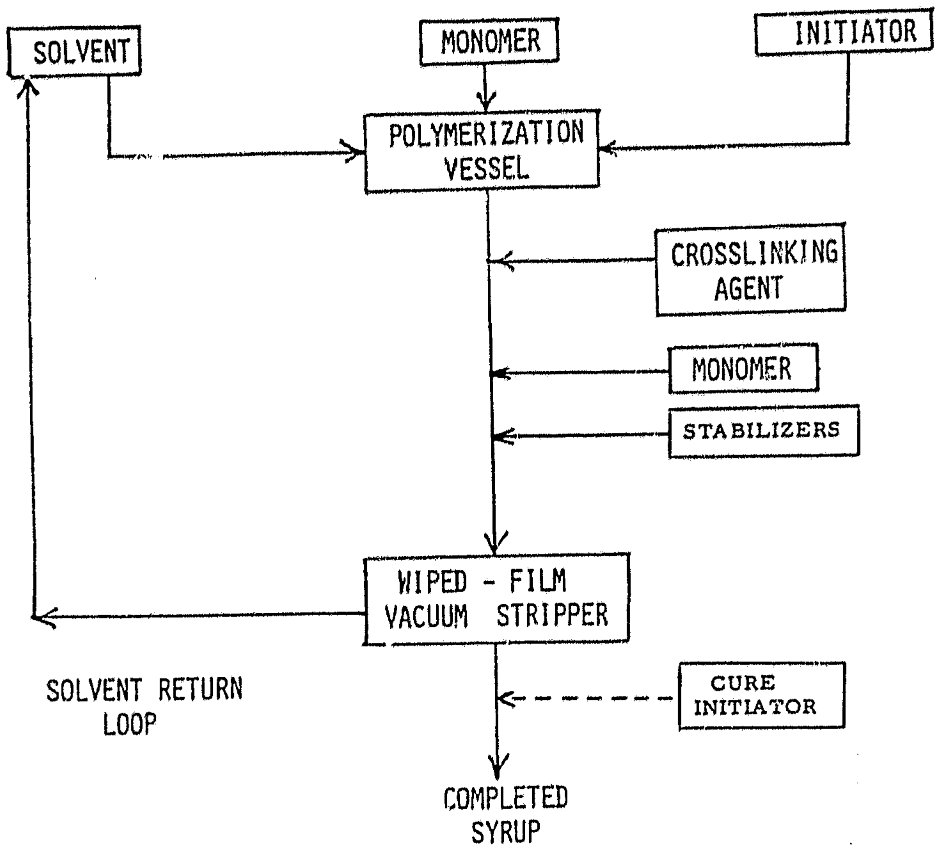
TENSILE STRENGTH (D638)	300	PSI
YOUNG'S MODULUS (D-638)	100	PSI
ULTIMATE ELONGATION (D638)	110	%
HARDNESS (SHORE A)	44	
GEL CONTENT	84	%
INTEGRATED TRANSMISSION	90	%
REFRACTIVE INDEX	1.47	
RESIDUAL VOLATILES	0.7	%

ODOR: ACCEPTABLE LOW

MAY BECOME ACCEPTABLE REPLACEMENT FOR RTV SILICONES

ENCAPSULATION TASK

NEW METHOD OF PRODUCTION:



- ELIMINATES THE RECOVERY OF DRY POLYMER AND PROCEEDS DIRECTLY TO SYRUP FORMULATION .
- INDUSTRIAL SAMPLES AVAILABLE - SPRINGBORN LABORATORIES
- PILOT PLANT QUANTITIES ALSO AVAILABLE - COST TO BE DETERMINED
- INITIATOR AND DATA SHEET SUPPLIED WITH EACH REQUEST
- PRIMER: TENTATIVE RECOMMENDATION
  DOW CORNING Z-6032 W
  (10% SOLUTION IN METHYL ALCOHOL)

Aliphatic Urethane Pottant (Casting Syrup)

COMMERCIAL SOURCES:

- H. J. QUINN, MALDEN, MASS.
  Q - 621 / Q - 626
- DEVELOPMENT ASSOCIATES
  N. KINGSTOWN, R.I.
  Z - SERIES PRODUCTS

DEVELOPMENT INTEREST: (NO COMMERCIAL PRODUCTS)

- MOBAY CHEMICAL CO., PITTSBURGH, PA.
- AMERICAN CYANAMIDE, BOUND BROOK, N.J.

REQUIRED TECHNOLOGIES:

- FASTER CATALYST SYSTEMS
- ADHESIVES / PRIMERS
- ANTIOXIDANTS - THERMAL STABILIZERS
- UV STABILIZERS
- PROOF OF PERFORMANCE
- 100 % ACTIVE
- LOW MOISTURE SENSITIVITY

(PROTOTYPE)

DEVELOPMENT ASSOCIATES, INC.

DESIGNATION: Z-2211

MIXED UNCURED SYRUP:	
VISCOSITY, CPS	500
GEL TIME, MINUTES	15
CURE	90°C / 15 MINUTES
CURED PROPERTIES:	
TENSILE STRENGTH, PSI	3,600
ELONGATION, %	200
YOUNG'S MODULUS, PSI	1,100
HARDNESS, SHORE D	60
INTEGRATED TRANSMISSION,%	91
GLASS TRANSITION, °C	-117
COLOR	NONE
CUTOFF WAVELENGTH, NM	360*
FIELD PERFORMANCE	6 YEARS

* CONTAINS UV STABILIZER SYSTEM

- AVAILABLE - DEVELOPMENT ASSOCIATES, INC.
  NORTH KINGSTOWN, R.I.
- COST: APPX. $3.00 PER POUND
  (MIXED SYSTEM)
- CONTACT: MR. BUD NANNIG
- PRIMER: TENTATIVE RECOMMENDATION
  DOW CORNING Z-6020
  (10% SOLUTION IN METHANOL)

Soiling Effects

DECAY IN OPTICAL TRANSMISSION
SITE: ENFIELD, CONNECTICUT

MATERIAL	% TRANSMISSION[A.] CONTROL	4 WEEKS	8 WEEKS
PYREX GLASS	92	90	90
SODA LIME GLASS	87	84	87
TEDLAR 100BG30UT	84	72	77
RTV 615	79	65	65
Q1-2577	74	65	64
SYLGARD 184	82	81	54

A. DIRECT RRANSMISSION FROM 350 NM TO 900 NM.

JPL SOILING THEORY SUGGESTS THAT SOIL RESISTANT SURFACES HAVE THE FOLLOWING PROPERTIES:

- HIGH SURFACE HARDNESS
- HYDROPHOBIC
- OLEOPHOBIC
- ION FREE
- LOW SURFACE ENERGY
- SMOOTH

Anti–Soiling Experiments

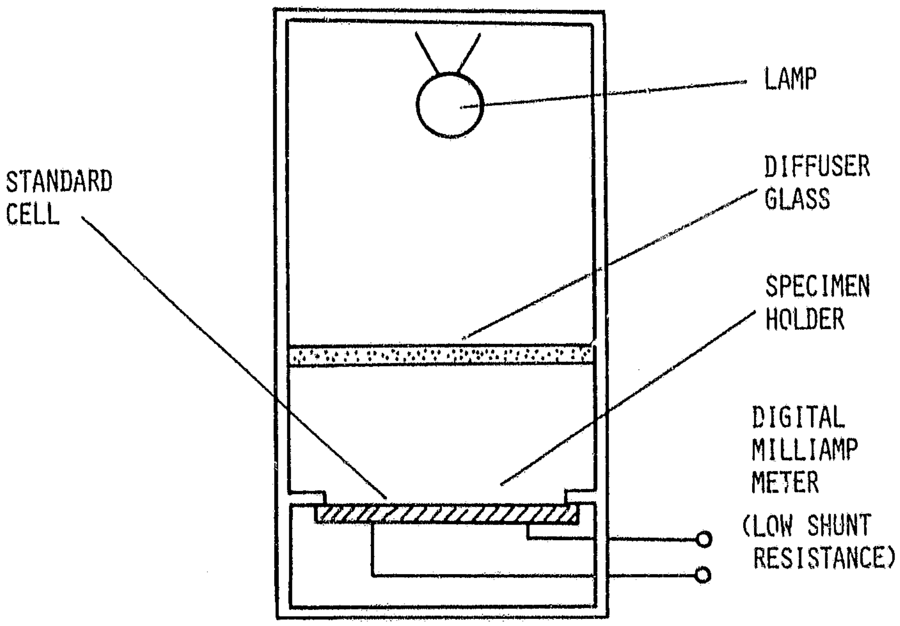
SURFACE UNDER INVESTIGATION:

- SUNADEX GLASS
- 3M ACRYLIC FILM, X-22417
- TEDLAR 100BG30UT - DU PONT

SURFACE TREATMENTS UNDER INVESTIGATION:

- 3M FLUOROSILANE TREATMENT L-1668[A]
- PERFLUORODECANOIC ACID BASED COATING[A] DOW CORNING E-3820
- OWENS ILLINOIS GLASS RESIN 650
- GENERAL ELECTRIC SHC - 1000
- ROHM & HAAS WL-81

A. ALSO USED WITH OZONE TREATMENT TO COUPLE TO ORGANIC SURFACES



$$\frac{\text{CURRENT W/SPECIMEN}}{\text{SHORT CIRCUIT CURRENT}} \times 100 = \%\ \text{CHANGE IN SHORT CIRCUIT CURRENT}$$

Anti–Soiling Test Results

TWO MONTH EXPOSURE,
ENFIELD, CONN.

CHANGE IN SHORT CIRCUIT CURRENT, I_{SC}

TREATMENT	SUNADEX		ACRYLIC X-22417		TEDLAR 100 BG 30 UT	
	INITIAL		INITIAL		INITIAL	
CONTROL NO TREATMENT	90.5	-1,8	84,0	-3,3	87,7	-2,9
L-1668	89,7	-1,1	80,3	-0,3	88,4	-1,3
L-1668/OZONE	A.		84,5	-2,1	88,1	-0,8
PFDA E-3820	90,0	-0,1	80,0	-1,3	86,0	0
PFDA E-2820/OZONE	A.		84,1	-1,7	86,0	-2,5
GLASS RESIN 650	91,0	-1,4	81,1	-2,2	89,0	-2,6
SHC -1000	91,9	-2,5	82,1	-4,3	89,0	-2,1
WL-81	90,7	-2,0	83,6	-2,9	87,7	-2,9

A. NOT PREPARED

GENERAL OBSERVATIONS:

- LOWEST LOSSES - SUNADEX AND TEDLAR WITH E-3820
- SUNADEX GLASS, LOWEST CONTROL LOSS, LOWEST OVERALL LOSS
- HIGHEST LOSS OF CONTROL FOUND FOR ACRYLIC FILM

Gasket Compounds

COMPOUNDED ELASTOMER	COST $/LB	COMPRESSION SET RECOVERY	COST/SET[A], RECOVERY INDEX $/%
SILICONE	$2.53	65 - 90%	2.81 - 3.89
ETHYLENE/VINYL ACETATE	$0.85	65 - 80%	1.06 - 1.31
NEOPRENE	$0.87	75 - 85%	1.02 - 1.16
EPDM	$0.58	70 - 90%	0.64 - 0.83

EPDM COMPOUNDS, ADVANTAGES:

- BEST COMPRESSION SET/COST RATIO
- LOW COST
- EASY EXTRUSION -- COMPLEX PROFILES
- DEMONSTRATED WEATHERABILITY
- HISTORY OF SUCCESSFUL USE IN RELATED APPLICATION (AUTOMOTIVE WINDSHIELDS)

A. FOR COMPARATIVE PURPOSES ONLY

Gasket Materials

- SUPPLIER OF GASKETS -
  PAWLING RUBBER COMPANY
  PAWLING, NEW YORK
- CONTACT: STEVE SMITH
- FORMULATION: EPDM NUMBER E 633
  (DEVELOPED ASSOCIATION WITH DU PONT)
- PAWLING SUPPLIES ABOUT 75% OF THE SOLAR INDUSTRY WITH GASKETS
- SERVICE TEMPERATURES: (-50°C TO)
  CONTINUOUS: 120°C
  INTERMITTANT: 150°C
- SERVICE LIFE: TWENTY TO THIRTY YEARS BASED ON RELATED FORMULATIONS
- SPECIAL EXTRUSIONS OR "OFF THE SHELF" PROFILES
- APPROXIMATE COST: $0.12 PER RUNNING FOOT -- DEPENDS ON VOLUME AND PROFILES
- DESIGNED FOR SOLAR COLLECTOR SEALING, HAS PASSED THE HUD 30 DAY STAGNATION TEST

PAWLING RUBBER COMPANY, E 633

TENSILE STRENGTH, PSI	2,200
ELONGATION, %	425
DUROMETER, SHORE A	60
TEMPERATURE RANGE, °C	-50 TO + 150
COMPRESSION SET, % 22 HOURS/70°C	20
WATER IMMERSION, % CHANGE 70 HOURS/100°C	0.5
FLEXIBILITY, BRITTLE POINT, °C	-40
OVEN AGING, 70 HOURS/100°C	
TENSILE CHANGE, %	-4
ELONGATION CHANGE, %	-10
OZONE RESISTANCE	OUTSTANDING
SUNLIGHT RESISTANCE	OUTSTANDING*

*PAWLING ESTIMATES SERVICE LIFE TO BE TWENTY YEARS MINIMUM BASED ON CLOSELY RELATED COMPOUNDS

Solar Module Sealants

TO PROVIDE FLEXIBLE CAULKING AND WATERPROOFING BETWEEN EDGE OF MODULE AND GASKET MATERIAL.

SURVEY OF INDUSTRIAL COMPOUNDS BEGUN:

COMPANY	PRODUCT	CHEMISTRY
TREMCO	PROGLAZE	SILICONE
TREMCO	MONO	ACRYLIC
TREMCO	440	BUTYL
3M	5354	BUTYL
3M	5376	BUTYL/POLYETHYLENE
THIOKOL	---	POLYSULFIDE
H.B. FULLER	1081	BUTYL

ALL HAVE LIFE EXPECTANCY OF 20 YEARS.

ENCAPSULATION TASK

CLASS	APPX. COST PER POUND	APPX. COST* PER MODULE
SILICONE	$ 3.50	$ 0.50
POLYAMIDES	$ 2.60	$ 0.30
POLYSULFIDES	$ 2.25	$ 0.27
POLYURETHANE	$ 2.25	$ 0.28
ACRYLICS	$ 1.70	$ 0.24
BUTYLS:		
TAPE COMPOUNDS	$ 3.67	$ 0.44
HOT MELT (NON-CURE)	$ 2.00	$ 0.24
HOT MELT	$ 1.62	$ 0.19

* 2 FOOT BY 4 FOOT MODULE (1/8 INCH BEAD OF SEALANT)

TENTATIVE RECOMMENDATIONS:

- TAPE STYLE, 3M 5354 BUTYL
- CAULK TYPE, TREMCO "GUNNABLE BUTYL"

REMAINING INVESTIGATION:

- CURE/NON-CURE
- APPLICATION
- TESTING
- COST PERFORMANCE OPTIMUM

Solar Module Gasket–Sealant

NEW MATERIAL FROM DU PONT MAY SERVE AS BOTH COMPONENTS.

VAMAC VMR - 5254, ETHYLENE/ACRYLIC ELASTOMER

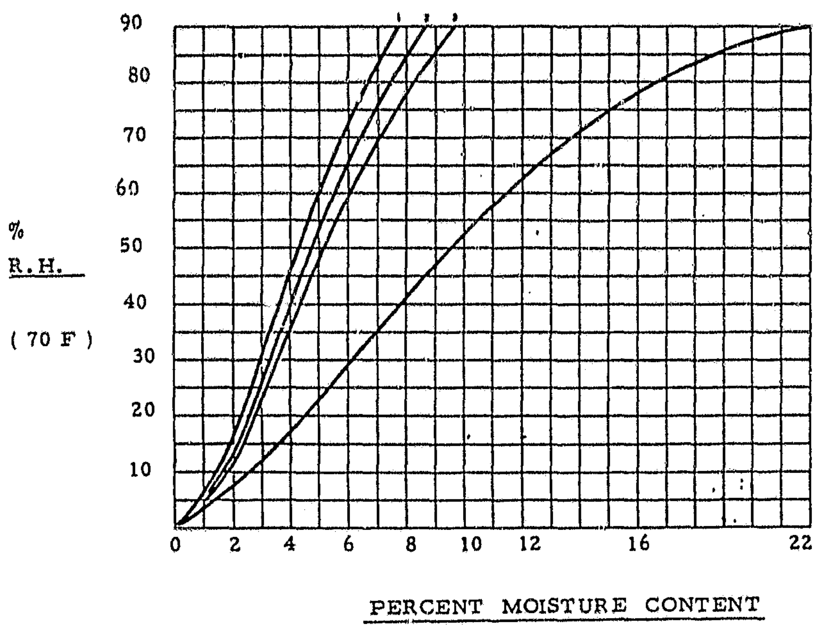
- HOT-MELT APPLICATION
- WATER, OIL, SOLVENT RESISTANCE
- VERY LOW MOISTURE VAPOR TRANSMISSION
- FLEXIBLE TO -60^{o}C
- GOOD ADHESION TO GLASS, METALS, RUBBERS, POLAR PLASTICS

Substrate Materials

MATERIAL	¢/FT^2	\$/M^2
COLD ROLLED MILD STEEL, 28 GAUGE	15.5	1.67
GLAVANIZED STEEL, G-90	24.5	2.64
SUPER DORLUX HARDBOARD (MASONITE CORPORATION)	14.0	1.51
DURON TEMPERED HARDBOARD (US GYPSUM CO.)	14.5	1.56

- SUBSTRATE ALLOCATION APPX. 70¢/FT^2
- COST INCREMENT WILL APPEAR FOR PROTECTIVE TREATMENT

Masonite Hardboard Products



2. SUPER DORLUX

- LINEAR COEFFICIENT OF HYGROSCOPIC EXPANSION 0.35 TO 0.4 % OVER 0 TO 100 % R.H. RANGE

Hardboard Protection Experiments

- WEIGHT LOSS OF HARDBOARDS AFTER EXPOSURE TO VACUUM BAG LAMINATION CYCLE

TREATMENT	RELATIVE HUMIDITY (AT EQUILIBRATION)	WEIGHT LOSS
CONTROL	50 %	4.85
EDGE SEAL W/ EPOXY	50 %	4.17 %
SURFACES SEALED W/KORAD EDGES SEALES W/EPOXY	50 %	3.04 %
ALUMINUM FOIL W/3M 4910 ADHESIVE	60 %	4.6 %
2 MIL STAINLESS FOIL W/ EVA 9918 ADHESIVE	55 %	3.13 %
TEDLAR 200 PT W/EVA 9919	60 %	2.19 %
TEDLAR 200 PT W/EMA A13439	60 %	2.2 %
ALUMINUM FOIL W/4910 ADHESIVE THEN EMA A 13439 W/TEDLAR 200 PT	60 %	1.9 %
SAME AS ABOVE	100 %	6.4 %
SURFACES SEALED W/ KORAD AND 4910 ADHESIVE, EDGES W/ EPOXY	100 %	6.78 %

- ALL SPECIMENS WERE 11" x 15" IN SIZE
- DIMENSIONAL CHANGE IN THE RANGE OF 0.05% TO 0.1% PER % WEIGHT LOSS

RS/4 Sunlamp Exposure

MATERIAL	HOURS	% PROPERTY RETAINED (ASTM D-638) TENSILE	ELONGATION
3M ACRYLIC FILM X-22417	5,700	54%	100%
EMA BASE RESIN (UNCOMPOUNDED)	5,000	10%	10%
EMA A11877 (COMPOUNDED)	5,000	100%	200%
DUPONT TEDLAR 100 BG 30 UT	5,000	100%	100%
BUTYL ACRYLATE BASE FORMULATION	4,000	N/A	N/A
FLUOREX - A	5,000	100%	100%
POLYURETHANE Z - 2341	1,000	100%	100%
REFERENCE:			
POLYETHYLENE UNSTABILIZED	500		10%
POLYPROPYLENE UNSTABILIZED	500		0%

EVA POTTANT

(NO COVER FILM)

- CLEAR STABILIZED EVA EXPOSED 22,700 HOURS NO OBSERVABLE CHANGE

	TOTAL INTEGRATED TRANSMISSION (%)	ULTIMATE* ELONGATION (%)	TENSILE* STRENGTH (PSI)
CONTROL	91	510	1890
EXPOSED 22,700 HRS.	90	560	1870

- UNSTABILIZED ELVAX 150 (EVA) BECOMES SOFT, TACKY, - LOSES PHYSICAL PROPERTIES IN LESS THAN 1,000 HOURS

* ASTM D-638

Thermal Aging Specimens, Air Oven Aging: EVA 9918

	CONTROL	90°C 10 MONTHS	130°C 10 MONTHS
TENSILE STRENGTH, PSI	2,100	2,100	144
ELONGATION, %	670	660	37
COLOR	CLEAR	CLEAR	CLEAR
% TRANSMISSION	91	92	74
TANGENT MODULUS, PSI	700	800	300
GEL CONTENT, %	70	92	88

*AIR OVEN AGING

PROCESS DEVELOPMENT AREA

D. B. Bickler, Chairman

Process Development Area progress and status reports included an introduction and detailed presentations on the two MEPSDU processes and individual contractor reports on other process developments.

MEPSDU

Westinghouse presented its MEPSDU Prototype Module Design Review in a workshop session, and during its process development presentation a summary of the module design was presented, as was material on SAMICS costing and alternative process developments.

The Solarex Corp. presentation covered its MEPSDU process, module design and input material selection. Technical progress included work on spray-dopant belt-furnace diffusion, optimized back-junction formation, spray AR processing and encapsulation process development.

Contract Review

The following highlights are summarized from the LSA contract review session, which also covered JPL in-house efforts on robotics, ion implantation, lamination and technology transfer.

Tracor MBA discussed robotics and computer-assisted assembly concepts being developed: cell-stringing by a robot, module layup, automated vacuum lamination and edge sealing. A videotape of equipment operation and a poster were presented.

Motorola Inc. has been working on process sequence developments in process technology, cell design and metallization. Its process technology efforts include surface preparation, etching and texturizing; substrate drying, and the handling of rectangular shapes. Plated metallization advances and thermal stress studies of metallized silicon were reported.

Photowatt International, Inc., is developing a metallization system using thick-film and electroplating technologies.

The RCA process sequence efforts are centered on the processing of upgraded metallurgical-grade silicon substrates.

The Bernd Ross Associates presentation addressed base-metal thick-film metallization adherent contacts using copper-lead-silver fluoride and copper-lead-carbon fluoride pastes.

Spectrolab, Inc., discussed progress on the Midfilm metallization process. A bimodal cell-efficiency plot was obtained that showed a contact-resistance problem; use of an indium-tin oxide AR coating solved it, and gave average cell efficiencies of 12%.

PROCESS DEVELOPMENT AREA

Junction formation by ion implantation and electron-beam pulse annealing was described by Spire Corp.

Westinghouse Electric Corp.'s efforts to provide base-metal contacts of evaporated titanium and nickel with electroplated copper have shown good electrical characteristics but poor adherence.

The University of Pennsylvania independent assessment of the MEPSDU processes has reached the final compilation and reporting stage.

JPL In-House Activities

Labor reduction and quality improvement are two areas of interest to the JPL robotics assembly effort. An improved computer vision system and force sensors have been developed.

Non-mass-analyzed ion implantation has been demonstrated by JPL and industry transfer is following.

Contractor-developed solar-cell processes are made available for industry evaluation by JPL. Since more processes are being developed, a continuing industry review is needed.

A progress report on JPL laminating process development and materials research was presented to an encapsulation session. Recent results have shown some adherent, chemically bonded surfaces.

MEPSDU

APPROACH TO LONG-LIFE PERFORMANCE

WESTINGHOUSE ELECTRIC CORP.

C.M. Rose

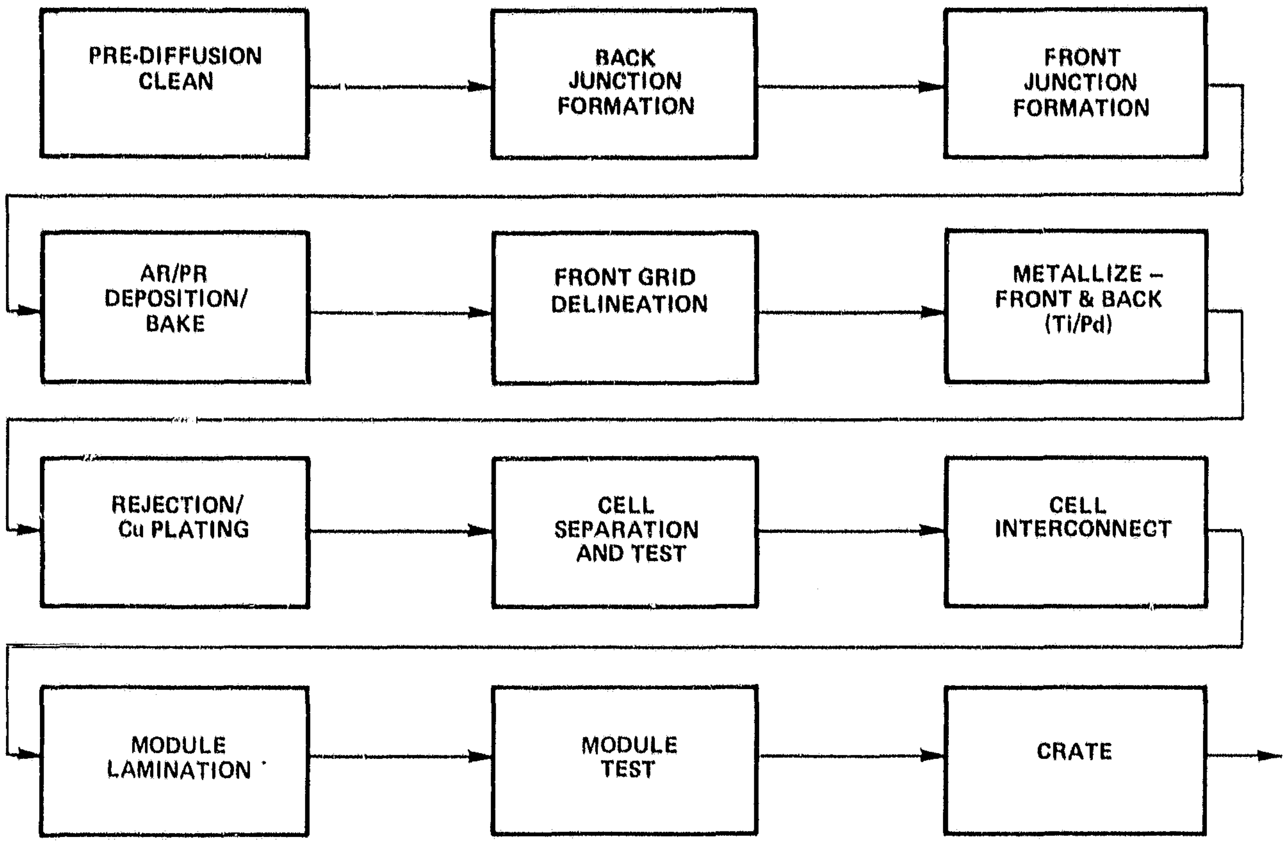
Contract Milestone Schedule

MILESTONE	ORIG. DATE	REVISED DATE
START DATE	NOV. 26, 1980	NOV. 26, 1980
PRELIMINARY DESIGN REVIEW	MAR. 3, 1981	MAR. 3, 1981
PROTOTYPE MODULE DESIGN REVIEW	JULY 1, 1981	JULY 14, 1981
MIDTERM DESIGN REVIEW	JULY 1, 1981	JAN. 14, 1982
MEPSDU DESIGN REVIEW	DEC. 1, 1981	MAY 15, 1982
MEPSDU INSTALLATION	JUNE 15, 1982	JAN. 31, 1983
TECHNICAL FEASIBILTY EXPERIMENTS	FEB. 15, 1983	DEC. 15, 1983
FINAL REPORT	MAR. 1, 1983	DEC. 31, 1983

Goals and Approach

- DESIGN MODULE MEETING JPL 5101-138 SPECIFICATIONS
- SELECT AND VERIFY PROCESS SEQUENCE FOR FABRICATING MODULES
- DESIGN AND BUILD A TEST FACILITY TO FABRICATE MODULES USING SELECTED PROCESS SEQUENCE
- PERFORM 3 TECHNICAL FEASIBILTY EXPERIMENTS
- ACCEPTANCE AND QUALIFICATION TESTING OF MODULES PRODUCED
- DETERMINATION OF 1986 MODULE PRODUCTION COSTS

Baseline Process Sequence



Cost Analysis - SAMICS

ASSUMPTIONS

1. 3 SHIFT, 345 DAYS/YEAR OPERATION
2. 12% MODULE EFFICIENCY AT 28^{o}C AND 100 mW/cm^2 INSOLATION
3. 90% CELL YIELD; 95% MODULE YIELD
4. 25 MW/YR PRODUCTION

Value Added per Process Step

PROCESS STEP	VALUE ADDED (1980$/WATT)
PRE-DIFFUSION CLEANING (INCLUDING INPUT SILICON DENDRITIC WEB)	0.320
BORON DIFFUSION	0.032
PHOSPHORUS DIFFUSION	0.027
DEPOSITION OF ANTI-REFLECTION AND PHOTORESISTS COATINGS	0.015
EXPOSURE/DEVELOPMENT/ETCH TO FORM GRID LINES	0.018
METALLIZE WEB	0.038
REJECTION/PLATING	0.039
CELL SEPARATION AND TESTING	0.035
CELL INTERCONNECTION	0.027
MODULE LAMINATION	0.141
CRATING OF MODULES	0.026
TOTAL	0.72

Alternative Process Sequence Steps Under Evaluation

- ION IMPLANTATION JUNCTION FORMATION
- LIQUID DOPANT JUNCTION FORMATION
- LOWER COST METALLIZATION SYSTEMS
  - ELECTROLESS NI DEPOSITED ON SI
  - ELECTROLESS NI DEPOSITED ON TI

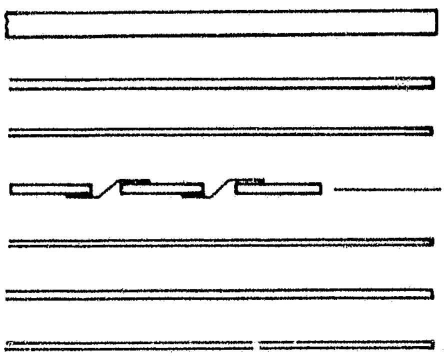
Cell Metallization Configuration

- TI/PD DIFFUSION BARRIER QUALIFIED FOR SPACE SOLAR CELL APPLICATIONS
- LONG-TERM EFFECTIVENESS OF BARRIER BASED ON 20 YEARS OF OPERATING DATA

Module Design Innovations

- USE OF DENDRITIC WEB SINGLE-CRYSTAL SILICON
- USE OF HIGH ASPECT RATIO (3.5:1) RECTANGULAR PHOTOVOLTAIC CELLS
- TEMPERED GLASS SUPERSTRATE
- FRAMELESS CONSTRUCTION
- ELIMINATION OF SOLDER JOINTS INSIDE THE ENCAPSULATION ENVELOPE
- HIGH CELL INTERCONNECT REDUNDANCY
- 12 PARALLEL CELL CIRCUITS

Module Layup



1/8" TEMPERED GLASS
.005" CRANEGLAS
.020" EVA
.006" SOLAR CELLS
.020" EVA
.005" CRANEGLAS
.003" MYLAR (KORAD)

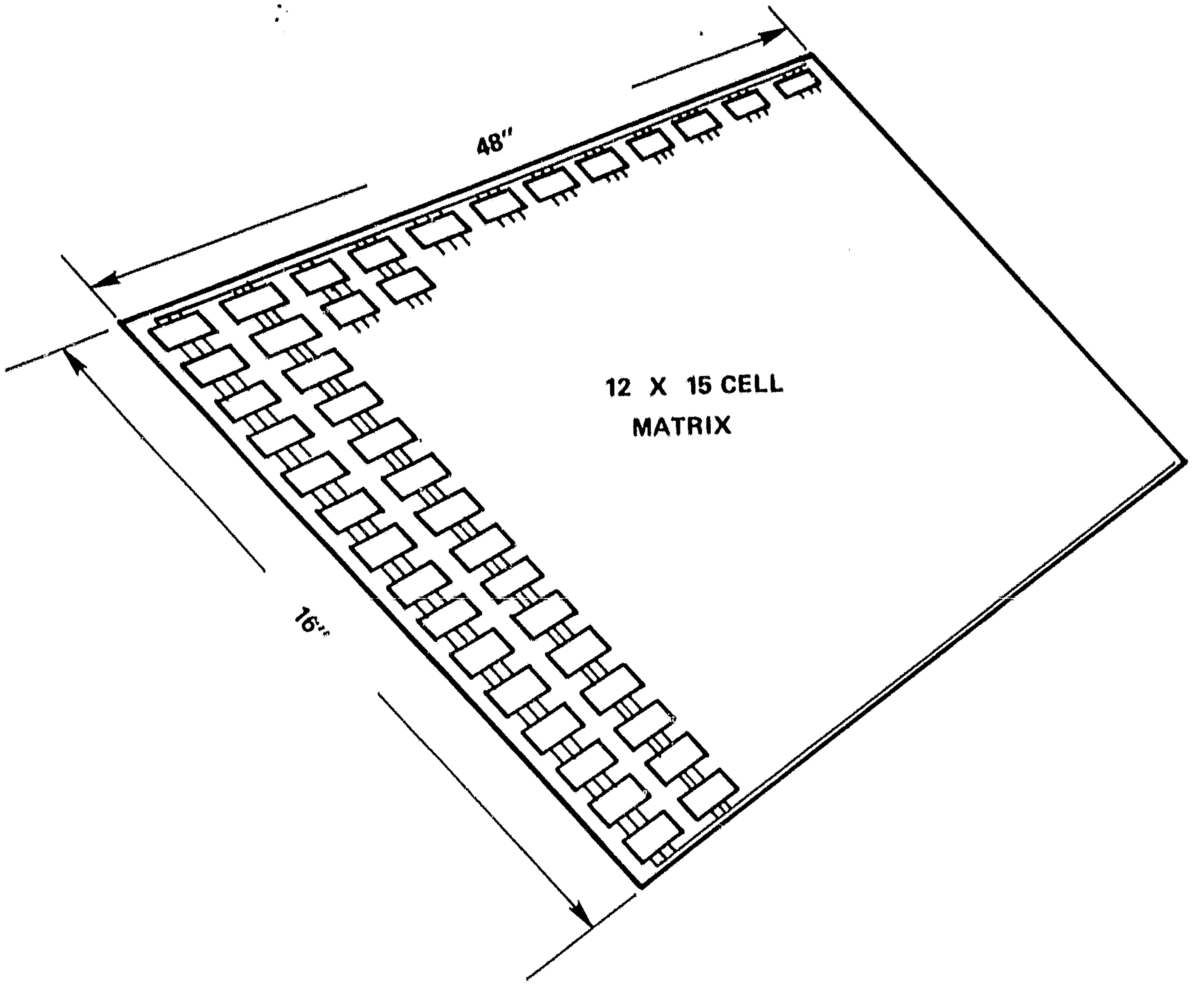
Module Layup Lifetime Considerations

• 1/8" TEMPERED GLASS	SURVIVED 1979 FT. COLLINS HAILSTORM
• CRANEGLAS	ASSISTS IN REMOVAL OF ENTRAPPED AIR DURING LAMINATION
• EVA POTTANT	ACCUMULATED OVER 16,000 HOURS WITHOUT DEGRADATION UNDER ACCEL. TESTS
• KORAD BACKING	GOOD ADHERENCE ACHIEVED. UV DEGRADATION SECONDARY. ALTERNATES UNDER INVESTIGATION.
• EDGE TAPES	VARIOUS CANDIDATES UNDER INVESTIGATION

Module Electrical Circuit

- 12 PARALLEL STRINGS OF 15 SERIES CONNECTED CELLS
  - NO CELL CARRIES OVER 9% OF MODULE CURRENT
  - CELL DAMAGE POTENTIAL DURING SHADED/SHORT CIRCUIT OPERATION ELIMINATED
  - NO DIODES REQUIRED
- LATERAL CONTACT OF CELLS WILL NOT AFFECT PERFORMANCE

PROCESS DEVELOPMENT AREA



Cell Electrical Interconnects

- ULTRASONIC BONDING REPLACES REFLOW SOLDERING
  - REDUCED ELECTRICAL CONTACT RESISTANCES MEASURED
  - FASTER PROCESS ALLOWS INCREASED BOND REDUNDANCY
  - NO FLUXES INTRODUCED INSIDE LAMINATED LAYUP
- INTERCONNECT FAILURE CONSIDERATIONS
  - EXTENSIVE ANALYSIS INDICATE THAT INTERCONNECT STRESSES CANNOT EXCEED ENDURANCE LIMIT
  - THERMAL CYCLE TESTING OF PROTOTYPE MODULES HAS CONFIRMED RESULTS
  - NEED FOR STRESS RELIEF ELIMINATED BY GEOMETRY

Maintainability Considerations

- AMP TERMINAL CONNECTIONS REQUIRE NO FIELD TOOLS
- REMOVAL OF MODULE FROM ARRAY IS ONE-MAN OPERATION
- NO EXPOSED METAL ON MODULE SURFACE

MEPSDU Module Operation

- MODULE OPERATING PARAMETERS AT 80 mW/cm^2; 20°C AMBIENT

OPEN CIRCUIT VOLTAGE	=	8.16 V
SHORT CIRCUIT CURRENT	=	7.52 A
POWER	=	44.9 W
EFFICIENCY	=	11.9 %
NOM OPERATING VOLTAGE	=	6.63 V

- MODULE OPERATING PARAMETERS AT 100 mW/cm^2; AM1.5, AND 28°C CELL OPERATING TEMPERATURE

POWER	=	59.6 W
EFFICIENCY	=	12.6 %

Conclusions

- Ⓦ MEPSDU PROJECT CURRENTLY ON SCHEDULE AND BUDGET
- ADDITIONAL PROCESS SEQUENCE STUDY WORK UNDERWAY IN REVISED PROGRAM PLAN
- Ⓦ MEPSDU MODULE DESIGN COMPLETED
  - MEETS JPL 5101-138 SPECIFICATIONS
  - LONG-LIFE PERFORMANCE, PRIMARY DESIGN CONSIDERATION
- PRELIMINARY ECONOMIC ANALYSIS (SAMICS) COMPLETED SHOWING COST EFFECTIVE PROCESS

MEPSDU

SOLAREX CORP.

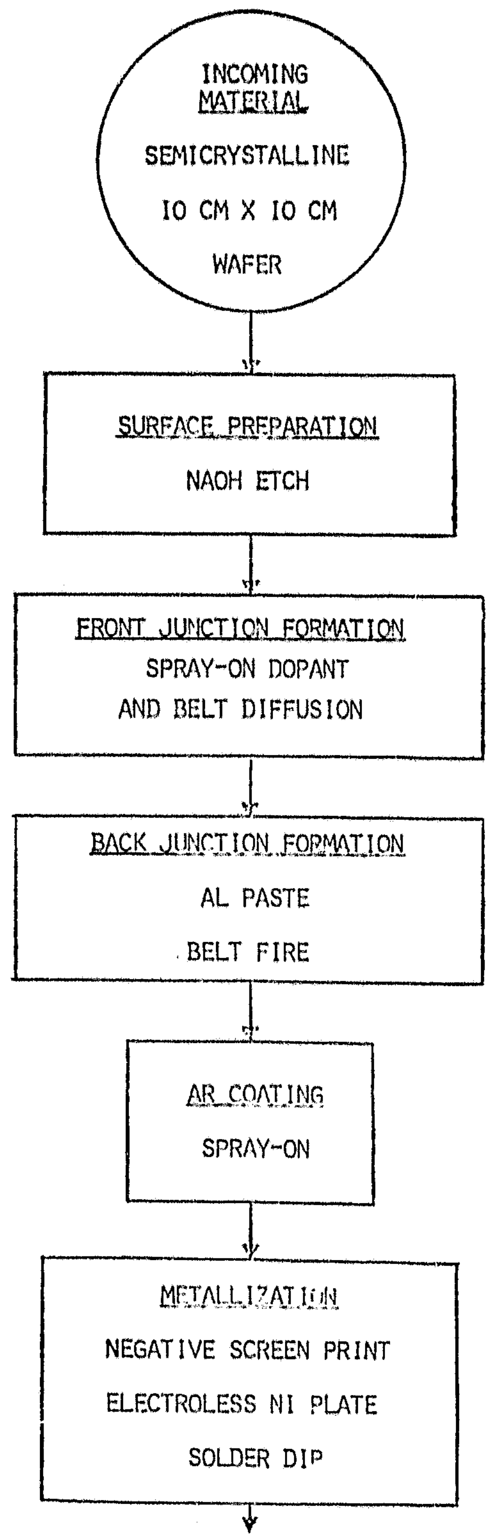
John H. Wohlgemuth

CONTENTS

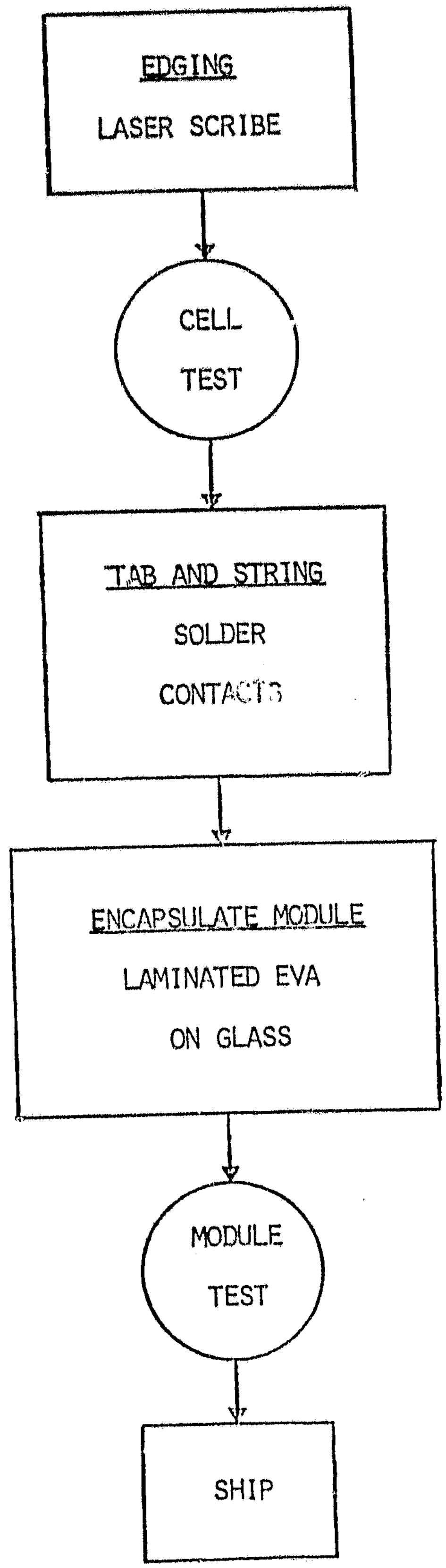
Design Philosophy

- USE PROCESSES THAT HAVE ALREADY BEEN VERIFIED, IN MOST CASES BY MORE THAN ONE CONTRACTOR.
- USE COMMERCIALLY AVAILABLE EQUIPMENT OR MODIFICATIONS OF SUCH EQUIPMENT.
- USE PRODUCTION EQUIPMENT, NOT LABORATORY-SCALE EQUIPMENT.
- NO MANUAL HANDLING OF CELLS.

General Process Description



PROCESS DEVELOPMENT AREA



Laser Scribe

USE OF LASER TRENCHING UNDER REEVALUATION. COMBINATION OF NEGATIVE SCREEN PRINTING METAL HALO AND LASER SCRIBING TRENCH RESULTS IN HIGH LIKELIHOOD OF SHORTING INTERCONNECT TO HALO.

FOUR ALTERNATIVES UNDER EVALUATION:

- OXIDE MASK EDGE TO PROTECT EDGE DURING DIFFUSION AND NI PLATING.
- PLASMA ETCH TO REMOVE N+ AND NI FROM EDGE ON LARGE STACK OF WAFERS.
- LASER SCRIBE ALL THE WAY THROUGH THE SILICON RATHER THAN TRENCHING.
- SCREEN PRINT ALL THE WAY TO THE EDGE AND STILL USE LASER TRENCHING.

Module Design

72 10 CM X 10 CM SEMICRYSTALLINE CELLS

2 PARALLEL - 36 SERIES

APPROXIMATE ENVELOPE DIMENSIONS

66 CM X 120 CM
26" X 49.6"

DESIGN VOLTAGE - 14.5 V

GLASS SUPERSTRATE

ETHYLENE VINYL ACETATE ENCAPSULANT

POLYETHYLENE VAPOR BARRIER

GASKET FOR MOUNTING (NO FRAME)

AMP OUTPUT CONNECTORS

INTERNAL DIODE PROTECTION - 3 DIODES PER MODULE

Module Design Rationale

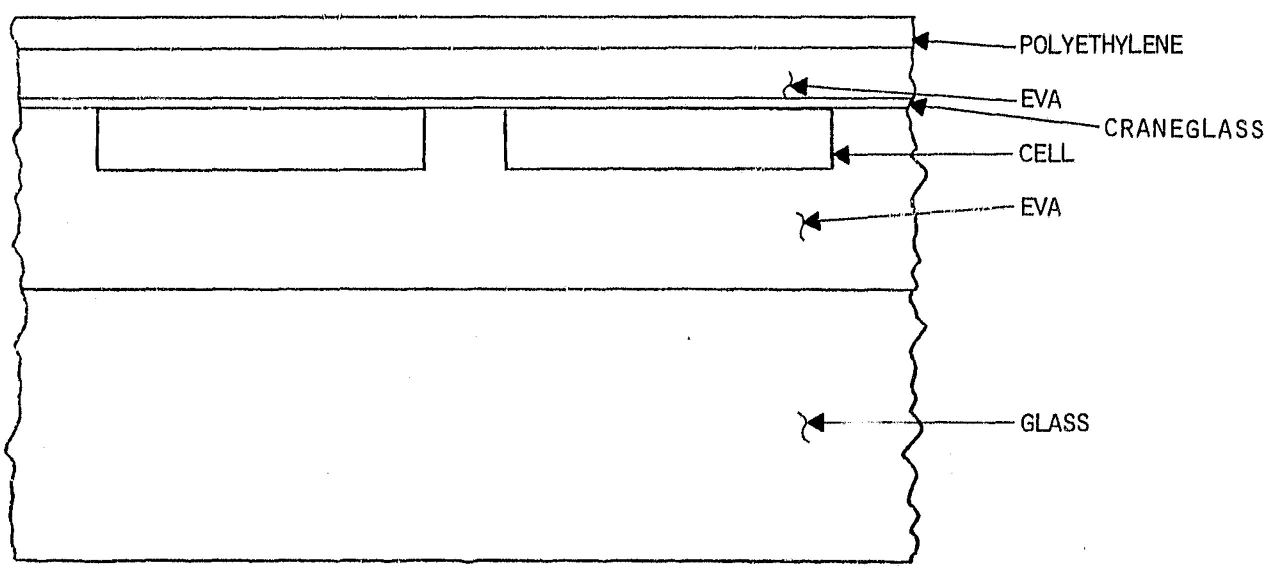
REQUIREMENTS:

- MODULE CAPABLE OF CHARGING 12 VOLT BATTERY.
- SIZE REASONABLY HANDLEABLE BOTH IN PRODUCTION EQUIPMENT AND IN FIELD, BUT LARGE ENOUGH FOR ECONOMIC PRODUCTION.
- PARALLELING TO PROVIDE RELIABILITY
- USE 10 CM X 10 CM SEMICRYSTALLINE CELLS
- PROVIDE DIODE PROTECTION

DESIGNS:

- USE 36 CELLS IN SERIES TO PROVIDE 14 TO 15 VOLTS OUTPUT AT PEAK POWER AND NOCT.
- USE 2 CELLS IN PARALLEL TO PROVIDE RELIABILITY.
- PLACE 72 CELLS IN 6 ROWS OF 12 CELLS EACH TO MAKE A MODULE CLOSE TO 2 FEET BY 4 FEET.
- PROTECT EACH PARELLEL SET OF 12 CELLS WITH A DIODE TO MINIMIZE DIODE COST BUT PROVIDE REQUIRED PROTECTION.

Module Cross Section



Glass Selection

ORIGINALLY SELECTED 1/8 INCH ANNEALED SODA-LIME GLASS.

- ANALYSIS SHOWED THAT FOR MODULE COSTS BELOW TWO DOLLARS PER WATT, THE LOWER COST OF SODA-LIME GLASS MORE THAN OFF SET THE REDUCED OPTICAL TRANSMISSION.
- HOWEVER, THE REDUCED STRENGTH OF ANNEALED SODA-LIME GLASS MAY COMPROMISE THE RELIABILITY OF THE MODULE TO MECHANICAL LOADING.

DECISION WAS TO USE 1/8 INCH TEMPERED LOW IRON GLASS AS BASELINE. HOWEVER, WE WILL CONTINUE TO EXPERIMENT WITH LOWER COST GLASS.

Interconnect Design

INITIAL PROPOSAL

- STANDARD OVER-UNDER DESIGN
- TWO PADS PER CELL ON ONE EDGE

PROBLEMS WITH THIS DESIGN

- NO CRACK TOLERANCE
- REDUCED CELL EFFICIENCY BECAUSE OF LARGE TRAVEL DISTANCE OF CARRIERS ACROSS CELL FACE
- MAYBE INSUFFICIENT STRESS RELIEF IN HIGH DENSITY PACKAGE

SOLUTION

- USE WRAPAROUND CONTACTS WITH FOUR PADS ON EACH CELL
- FOUR TAKE-OFF POINTS ON FRONT AND BACK PROVIDE CRACK TOLERANCE .
- USING TWO PADS ON TWO OPPOSITE EDGES BREAKS 10 X 10 INTO FOUR 5 X 5S, RESULTING IN HIGHER CELL EFFICIENCY
- WRAPAROUND AND IN PLANE STRESS RELIEF IMPROVES STRESS RELIEF PROPERTIES

Module Layout

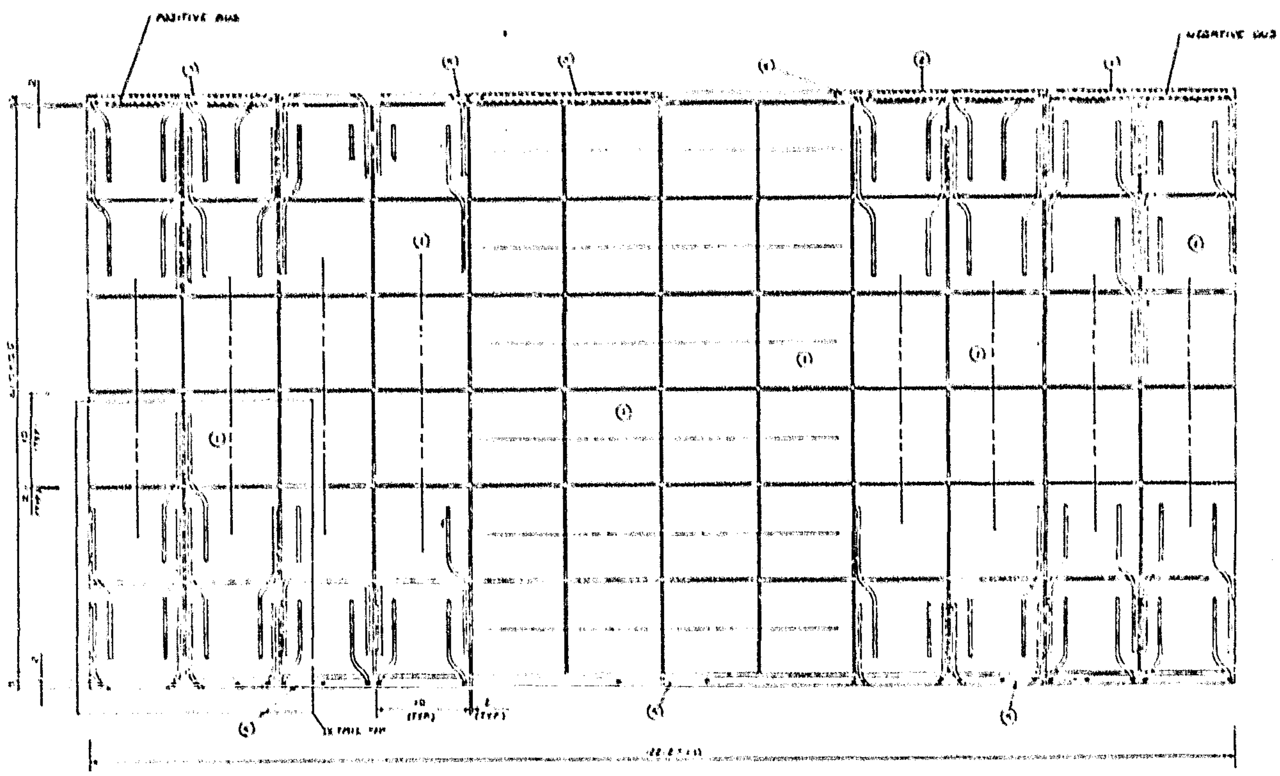
INITIAL MODULE DESIGN CALLED FOR SERIES STRINGS OF TWELVE CELLS ALONG FOUR FOOT DIMENSIONS WITH PARALLEL CROSS-STRAPS OF PAIRS OF STRINGS EVERY THREE SERIES PAIRS AND DIODES PROTECTING EACH DOUBLE STRING OF TWELVE CELLS.

THIS DESIGN HAD TWO MAIN PROBLEMS:

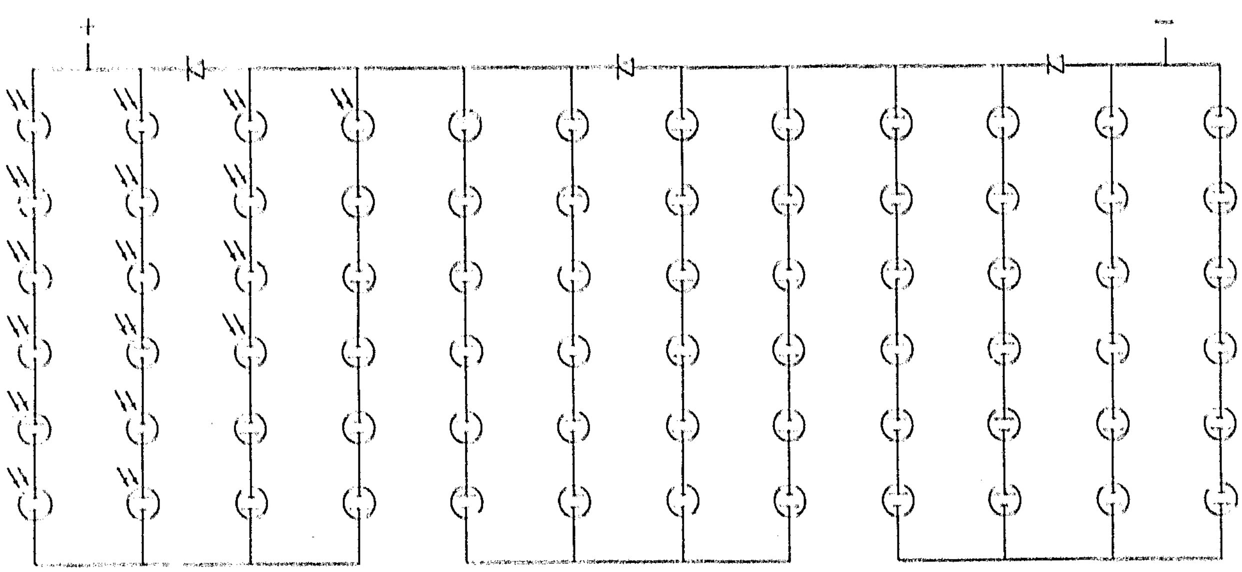
- PARALLEL CROSS-STRAPPING THREE CELLS ADDED SIGNIFICANT COMPLICATION TO THE TABBING AND STRINGING MACHINE.
- DIODE CONFIGURATION REQUIRED A WIRE TRAVELING THE LENGTH OF THE MODULE BETWEEN CELL STRINGS.

TO ALLEVIATE THE PROBLEMS, SERIES STRING SIX CELLS ALONG TWO FOOT DIMENSIONS. RETAIN TWO CELLS IN PARALLEL, BUT ONLY CROSS-STRAP AT BUSES. MOUNT DIODES IN BUS BARS WITH ONLY SHORT TABS BETWEEN BUSES.

Cell Assembly



Electrical Schematic



Wafer Size and Tolerances

NOMINAL SIZE

10.0 CM X 10.0 CM

ACCEPTABLE LENGTH OF ANY EDGE

9.97 CM TO 10.03 CM

RECTANGULARITY

$90^{\circ} \pm 0.5^{\circ}$

CORNER CROP

BETWEEN 3/32" AND 1/8" ON EACH CORNER

THICKNESS

0.012" TO 0.016"

TAPER

THICKNESS VARIATION IN ONE WAFER
LESS THAN 0.003"

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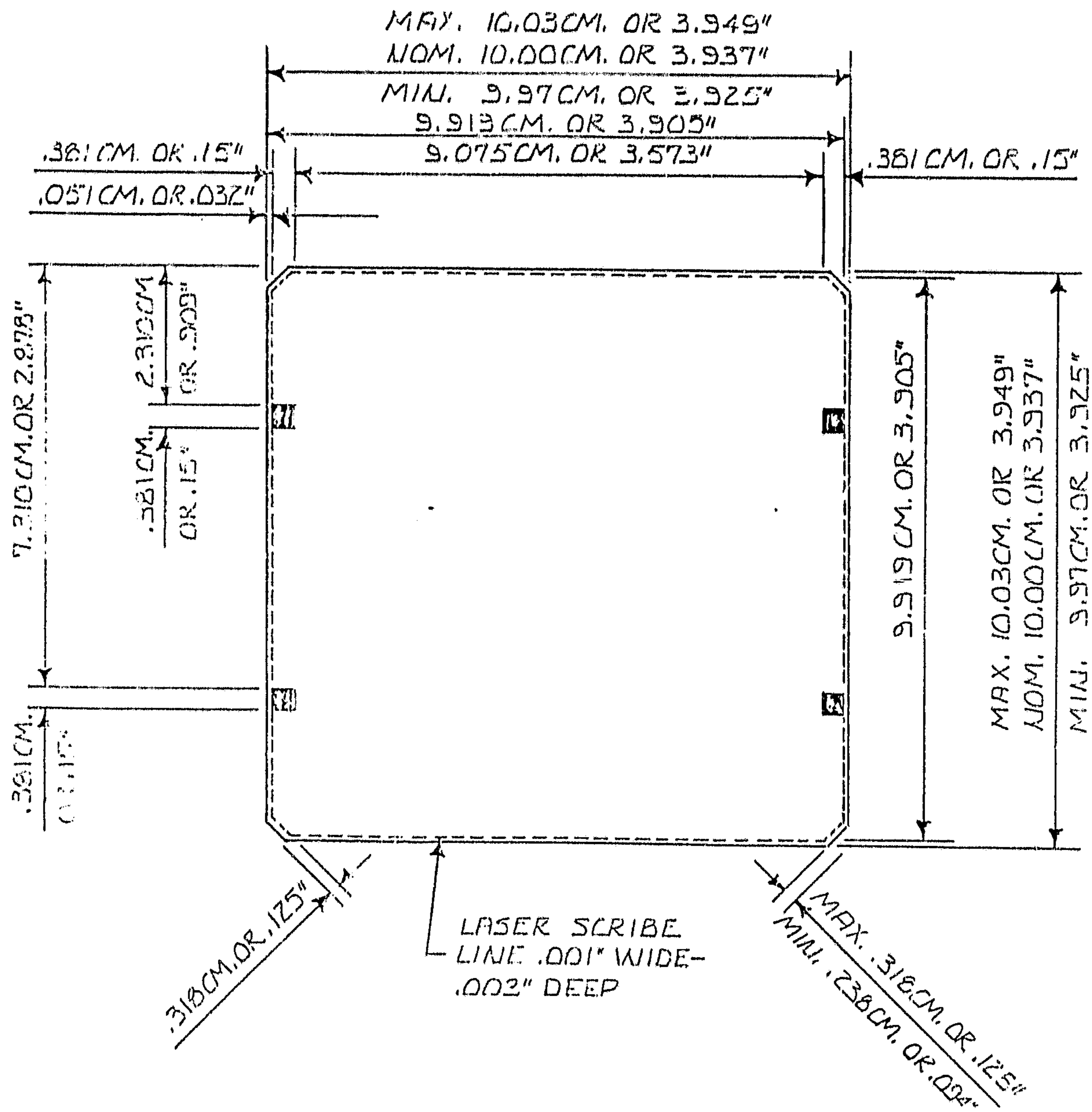
Cell Outline & Pad Placement



Electrical Requirements

TYPE

"P" TYPE

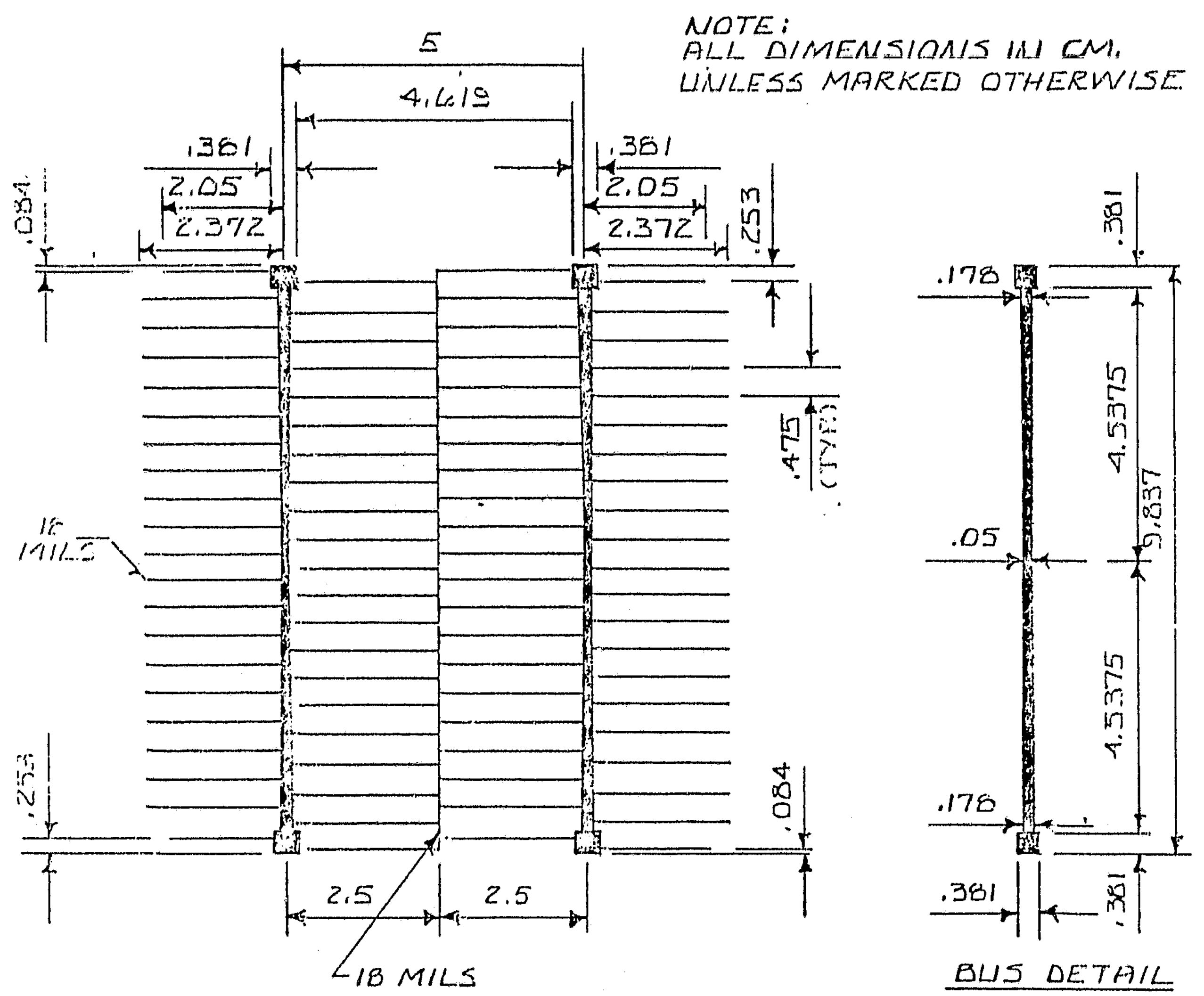
RESISTIVITY

0.5 OHM-CM TO 10.0 OHM-CM

LIFETIME

MINIMUM OF 4 μ SECOND LIFETIME

10 x 10-cm Grid Pattern



Technical Progress

- PRELIMINARY PROCESS, MODULE AND EQUIPMENT DESIGN
- DEVELOPMENT OF SPRAY DOPING - BELT DIFFUSION PROCESS
- OPTIMIZATION OF BACK JUNCTION FORMATION
- BACK CLEANUP EXPERIMENTATION - HCL ETCH OR GLASS BEAD SPRAY
- DEVELOPMENT OF SPRAY AR PROCESS
- RESIST INK EXPERIMENTS
- METALLIZATION TAB PULL TESTS
- ENCAPSULATION PROCESS DEVELOPMENT AND MATERIALS INVESTIGATION
- PRELIMINARY CELL FABRICATION AND TESTING

Diffusion Process

SPRAY DOPING

MUST USE OXYGEN OR AIR FLOW OR DIFFUSION OXIDE IS IMPOSSIBLE TO REMOVE.

USE VERY LITTLE DOPANT FOR EASE OF OXIDE REMOVAL. CELL PERFORMANCE INSENSITIVE TO AMOUNT OF DOPANT AS LONG AS ENTIRE WAFER SURFACE IS WETTED.

CELL PERFORMANCE INDISTINGUISHABLE BETWEEN SPRAY DOPING AND GASEOUS DIFFUSION FOR SAME TUBE DIFFUSION PROCESS.

SMALL AREA SEMICRYSTALLINE CELLS MADE USING SPRAY DOPANT WITH EFFICIENCY GREATER THAN TWELVE PERCENT AM1.

Diffusion Temperature Experiments: 10-min Diffusion Time

TEMPERATURE (°C)	SHEET RESISTANCE (Ω/□)	EFF (SINGLE CRYSTAL) NO AR (%)
870	72	10.1
880	56	10.3
890	41	9.5
900	38	9.8
910	32	8.5

EXPERIMENTING WITH ELECTROLESS NI AT SHEET RESISTANCE UP TO 60 Ω/□ - INITIAL RESULTS ENCOURAGING.

Belt vs Tube Diffusion

TUBE ≈ 15 PERCENT MORE POWER THAN BELT.

NOW OPTIMIZING BELT DIFFUSION PARAMETERS.

Back-Junction Formation

AL PASTE ALLOY AT 850°C.

USE DIFFERENT SCREEN SIZES AND ALLOY TIMES.

SCREEN SIZE	ALLOY TIME (SEC)	EFF (%)
80	20	13.1
80	30	13.75
100	20	13.55
150	20	13.4
200	20	10.1
250	20	7.4

NEED LARGE SCREEN OPENINGS WITH LONGER ALLOY TIMES. HOWEVER, MUST COMPROMISE WITH WARPAGE OF WAFERS FOR THICKER AL PASTE. WILL PROBABLY USE 100 MESH SCREEN.

Back Cleanup

FSI ETCH-STRIP MACHINE (2120)

PROCESS:		
	HCL (60°C)	300 SEC.
	DI RINSE	180 SEC.
	HF ETCH	60 SEC.
	DI RINSE	120 SEC.
	SPIN DRY	150 SEC.

PROBLEMS:

IR TRANSMISSION TESTS SHOW 300 SEC. HCL CLEANUP IS NOT SUFFICIENT CLEANUP TO MAKE ADEQUATE SOLAR CELLS.

AT 60°C HCL DEGRADES RAPIDLY, REQUIRING EXCESSIVE MATERIAL AND LONG HEAT-UP TIMES.

PROCESS DEVELOPMENT AREA

Glass Bead Cleanup

STANDARD SANDBLASTING EQUIPMENT USING GLASS BEADS SATISFACTORILY REMOVES CONTAMINATION BUT LEAVES MOST OF AL.

SUBSEQUENT NI PLATING GIVES GOOD ADHERANCE. PULL STRENGTHS FROM 11.5 TO 35 OZ, 326 TO 992 GRAMS.

CELLS HAD HIGHER EFFICIENCIES THAN STANDARD HCL CLEANUP AND SOLDER DIP ON BOTH SIDES.

Spray AR

AVERAGE FILM THICKNESS - 850 Å ± 100 Å

INDEX OF REFRACTION - 2.1 TO 2.2

CONSISTENT BLUE COLOR ON POLISHED SURFACE.

ON NAOH ETCHED SEMICRYSTALLINE SI GET GRAY COLOR WITH APRROXIMATELY 16 PERCENT REFLECTION.

UPON ENCAPSULATING GAIN 7 TO 15 PERCENT SHORT CIRCUIT CURRENT.

TRY TO PRETREAT WAFER TO YIELD MORE UNIFORM AR THICKNESS. SO FAR MATERIALS EITHER EVAPORATE TOO FAST HAVING NO EFFECT OR DRY TOO SLOWLY, LEAVING UNEVEN DEPOSITS OF TIOX.

Resist Ink

MUST BE CAPABLE OF:

- SURVIVING AR COATING ETCH
- SURVIVING NI PLATING BATH
- BEING SCREEN PRINTED EASILY WITH GOOD CONTROL.
- CURING QUICKLY
- NOT BLEEDING INTO THE PATTERN AREA DURING PROCESSING
- BEING EASILY AND COMPLETELY REMOVED.

LOOKED AT A LARGE NUMBER:

WARNOW	UNIVERSAL COLOR DISPERSION
HILTON-DAVIS	MACDERMID
CHROMA-CHEM	COLONIAL
INMONT	HOMEMADE FROM ACRYLOIDS AND BUTYL CELLUSOLVE

Select Colonial Resist ER-6055

CLEANUP IN EITHER: TRICHLOROETHYLENE
1,1,2-TRICHLOROETHANE
METHYLENE CHLORIDE

EACH WORKS WELL WITH GOOD ULTRASONIC AGITATION. (CASSETTES TEND TO ABSORB A LOT OF ULTRASONIC ENERGY.)

Tab Pull Tests

USE LOW TEMPERATURE SOLDERING IRON (600°C)

CONSISTENT HIGH PULL STRENGTHS FOR NI-SOLDER.

- ALMOST NONE BELOW 7 OZ.
- MANY ABOVE 20 OZ.

NO EFFECT FROM HEATING AT 150°C FOR ONE HOUR (LAMINATION CONDITIONS).

Encapsulation

CURE TESTS

TESTING OF EVA TO DETERMINE TIME-TEMPERATURE CURE RELATIONSHIP

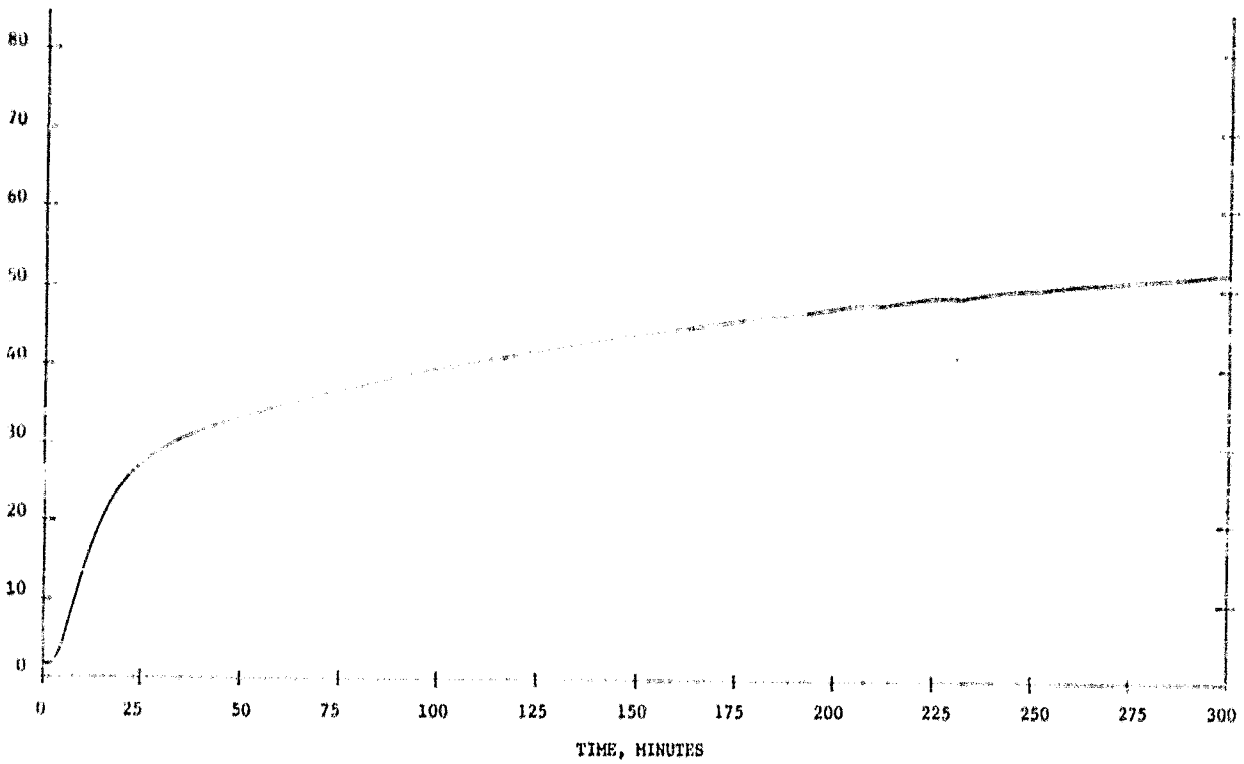
USE OSCILLATING DISC RHEOMETER (ODR) TEST - DONE BY MONSANTO. SEE RESULTS ON GRAPHS FOR 140°C AND 150°C

AT 140°C, 70-75% CURE - 96 MINUTES
AT 150°C, 70-75% CURE - 30 MINUTES

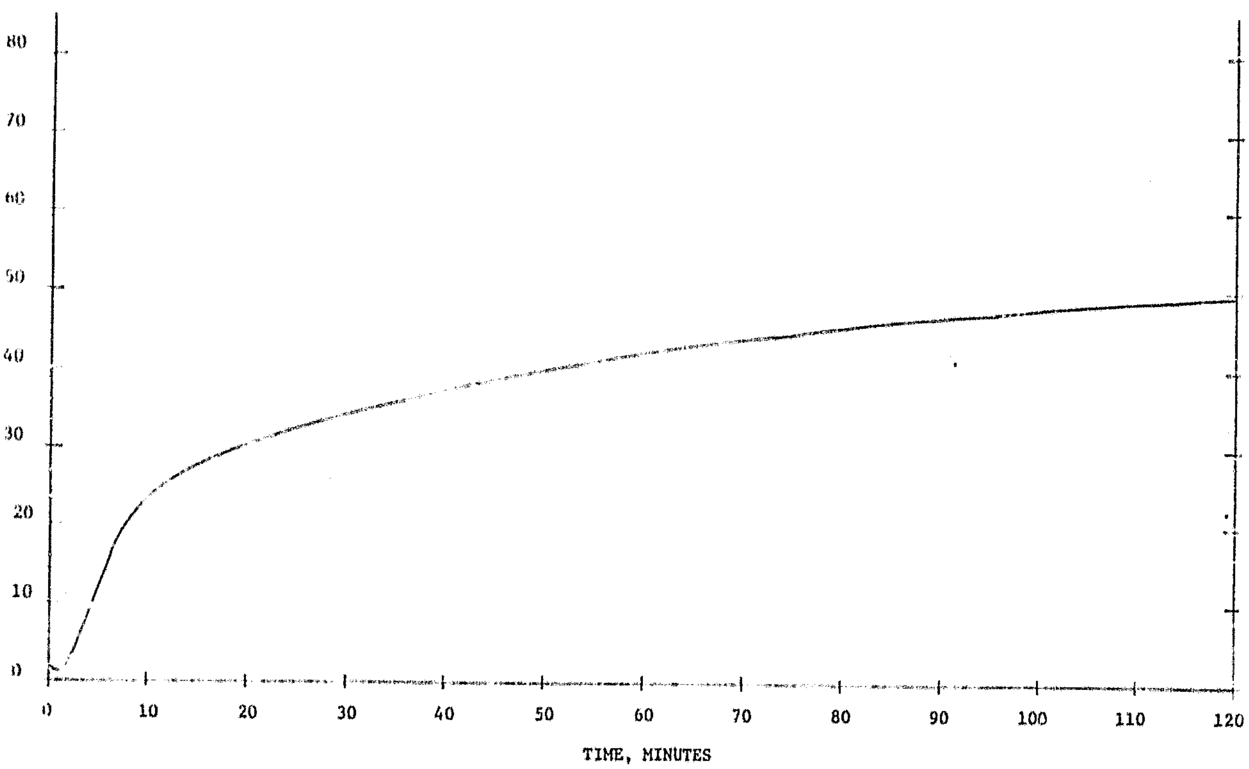
RESULTS AGREE WITH SPRINGBORN DATA.

CREEP TESTS AT 70°C AND 90°C INDICATE THAT 70-75% CURE REQUIRED SO THAT CELLS DO NOT MOVE AT A SIGNIFICANT RATE.

ODR Test at 140°C



ODR Test at 150°C



Cure Process

DURING LAMINATION, GAS BY-PRODUCT IS EVOLVED.

IF LAMINATION PRESSURE IS TOO LOW, THEN GAS WILL NOT BE EXPELLED FROM EVA AND BUBBLES RESULT.

SO OPTIONS ARE HIGHER PRESSURE - HIGHER TEMPERATURE - SHORTER CURE TIME

LOWER PRESSURE - LOWER TEMPERATURE - LONGER CURE TIME

NOW USING 7-10 LB/SQ FT - 150°C - 30 MINUTES

Polyethylene Vapor Barrier

GOOD PUNCTURE RESISTANCE

LOW PERMEABILITY TO WATER VAPOR

LONG LIFETIME

SUFFICIENT DIELECTRIC STRENGTH

COMPATABILITY WITH PROCESSES AND MATERIALS (EVA)

VERY LOW COST

PROBLEMS WITH SHRINKAGE

- PROPER SELECTION OF MATERIAL
- PROPER LAYUP AND LAMINATION RESULTS IN UNIFORMLY GOOD BACK COVERING WITH EXCELLENT ADHESION

Insulation Tapes

SINGLE SIDED ADHESIVE TAPES THAT ADHERE TO CELL AND EVA AS WELL AS PROVIDING THE REQUIRED ELECTRICAL ISOLATION.

POLYKEN -	POLYETHYLENE TAPE WITH ACRYLIC ADHESIVE 832
PERMACEL -	POLYESTER TAPE WITH ACRYLIC ADHESIVE P280
ADHESIVE RESEARCH -	POLYESTER TAPE WITH ACRYLIC ADHESIVE S5913
3M -	POLYESTER TAPE WITH ACRYLIC ADHESIVE 480
SHUFORD -	POLYPROPYLENE WITH ACRYLIC ADHESIVE PS748

ALL ARE NOW UNDERGOING ENVIRONMENTAL TESTS.

Cell Fabrication

PRELIMINARY FABRICATION OF 10 CM X 10 CM CELLS BY MEPSDU LABORATORY PROCESS

AVERAGE LOT EFFICIENCIES AS HIGH AS 8.8% HAVE BEEN OBTAINED.

UPON ENCAPSULATION, SHORT CIRCUIT CURRENT AND MAXIMUM POWER INCREASE FROM 7 TO 15%.

SO LOT AVERAGES AS HIGH AS 9.5 TO 10% HAVE BEEN OBTAINED BEFORE OPTIMIZATION OF THE PROCESSES.

Efficiency of Semicrystalline Material

SMALL AREA SAMPLES (2 CM X 2 CM)

BEST - 17%

BEST LOT AVERAGE - 16.5%

LARGE AREA SAMPLES (9.5 CM X 9.5 CM)

BEST - 13.5%

BEST LOT AVERAGE - 12%

TYPICAL PRODUCTION

10 - 11% LOT AVERAGE

ALL EFFICIENCIES MEASURED AT 100MW/CM^2 - AMI - 25^{o}C.

PRE-PROTOTYPE CELLS - 10-11%

PROTOTYPE DEV. CELLS - 11-12%

TDR CELLS - 12%

LONG TERM PRODUCTION GOAL - 15%

AREAS REQUIRED FOR IMPROVEMENT

- DIFFUSION TO IMPROVE OPEN CIRCUIT VOLTAGE AND BLUE CURRENT.
- ALLOY PROCEDURE TO IMPROVE OPEN CIRCUIT VOLTAGE AND RED CURRENT
- FRONT SURFACE PASIVATION TO IMPROVE OPEN CIRCUIT VOLTAGE
- CONTROL OF NARROWER METALLIZATION TO REDUCE SHADOWING AND IMPROVE FILL FACTOR
- IMPROVED LIFETIME OF SEMICRYSTALLINE SILICON

FIRST 4 WILL BE ADDRESSED IN THIS PROGRAM.

LAST IS BEING ADDRESSED IN DOE COOPERATIVE AGREEMENT.

TYPICAL CELL VALUES FOR TDR

EFF. = 12%	
POWER = 1.2 WATTS	AT AM1
VOC = 0.59 VOLTS	100 MW/CM^2
ISC = 2.75 AMP	25^{o}C
VMAX POWER = 0.47 VOLTS	
IMAX POWER = 2.55 AMP	

FROM PREVIOUS EXPERIENCE INCLUDING BLOCK IV -

TEMPERATURE COEFFICIENTS FOR CELL ARE:

$$\frac{\Delta V}{\Delta T} = -2.4 \text{ (mV/}^o\text{C}$$

$$\frac{\Delta I}{\Delta T} = +2.25 \text{ (mA/}^o\text{C)}$$

SO AT 50^{o}C

EFF. = 10.7%	
POWER = 1.07 WATTS	AT AM1
VOC = 0.53 VOLTS	100 MW/CM^2
ISC = 2.81 AMP	50^{o}C
VMAX POWER = 0.41 VOLTS	
IMAX POWER = 2.6 AMP	

Module Performance

NOCT

BLOCK IV MEASUREMENT - 56°C

HOWEVER THIS WAS MEASURED AT 100 mW/cm^2 WHILE MEPSDU SPEC (5101-138) CALLS FOR MEASUREMENT AT 80mW/cm^2.

ESTIMATE THAT THIS MAY MAKE 6° DIFFERENCE.

SO USE 50°C AS PRELIMINARY VALUE

ESTIMATED MODULE EFFICIENCY - TDR

72 CELLS 10CM X 10CM

2 PARALLEL - 36 SERIES

EXPECT TO HAVE REDUCTION IN POWER DUE TO MISMATCH OF CELLS. ASSUME TWO PERCENT LOSS FROM SUM OF CELL OUTPUTS.

TYPICAL MODULE OUTPUT AT ROOM TEMPERATURE:

EFF	= 10.1% (MODULE AREA)	
EFF	= 11.75% (CELL AREA)	
POWER	= 84.6 WATTS	AT AM1
Voc	= 21.2 WATTS	100 mW/cm^2
Isc	= 5.44 AMP	25°C
VMAX POWER	= 16.75 VOLTS	
IMAX POWER	= 5.05 AMP	

TEMPERATURE COEFFICIENTS FOR MODULES

$$\frac{\Delta V}{\Delta T} = -86.4 \text{ (mV/}^{\circ}\text{C)}$$

$$\frac{\Delta I}{\Delta T} = 4.5 \text{ (mA/}^{\circ}\text{C)}$$

TYPICAL MODULE OUTPUT AT NOCT

EFF = 9% (MODULE AREA)

EFF = 10.5% (CELL AREA)

POWER = 75.3 WATTS

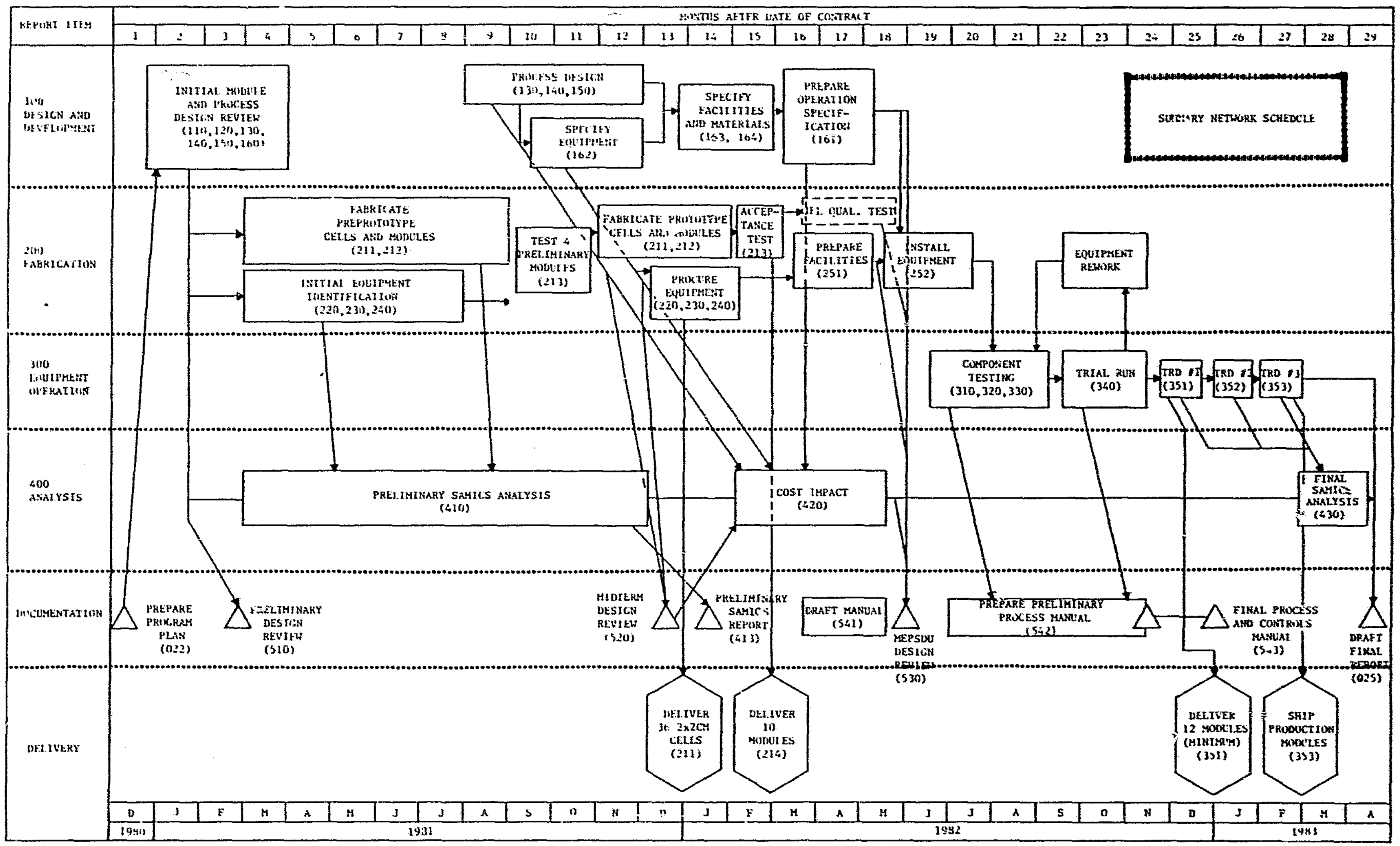
V_{OC} = 19.0 VOLTS

I_{SC} = 5.55 AMP

$V_{MAX\ POWER}$ = 14.6 VOLTS

$I_{MAX\ POWER}$ = 5.16 AMP

Schedule



PROCESS DEVELOPMENT AREA

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PROCESS DEVELOPMENT AREA

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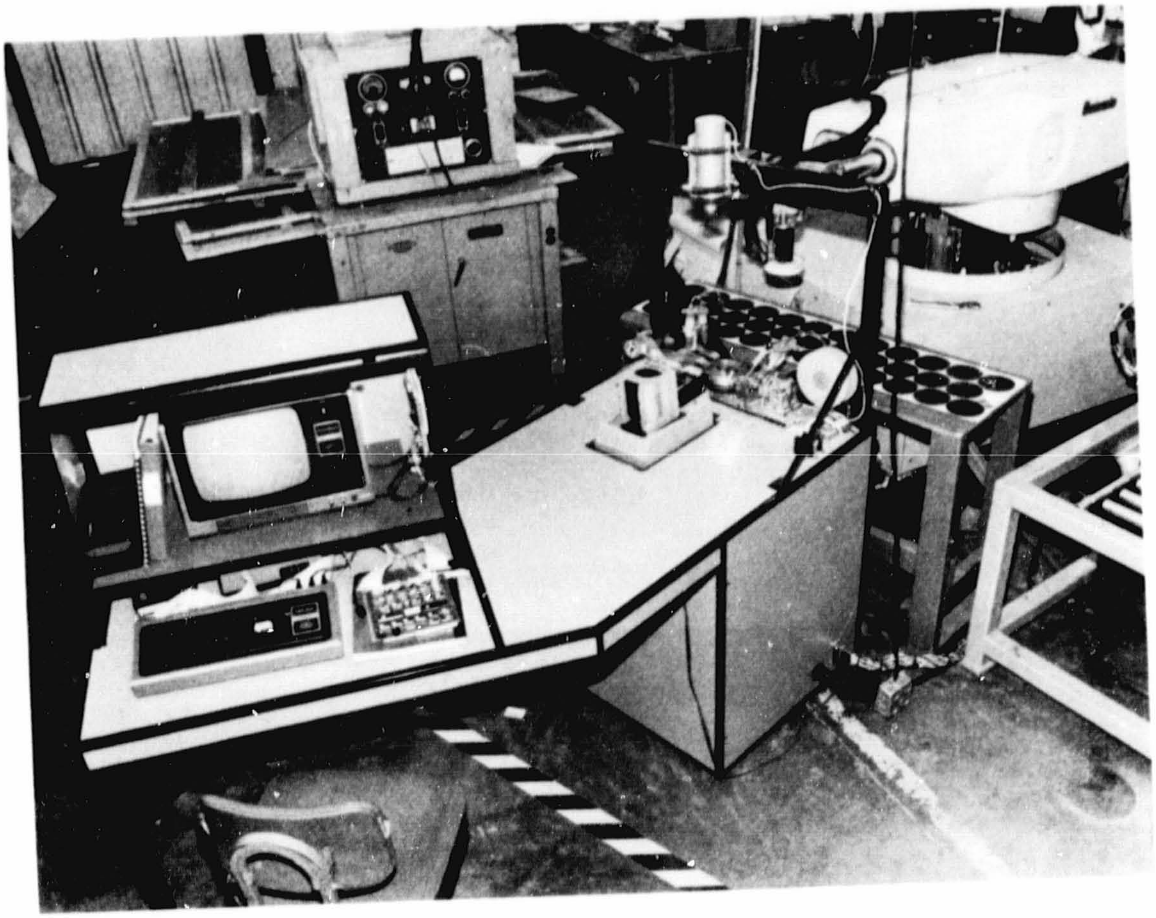
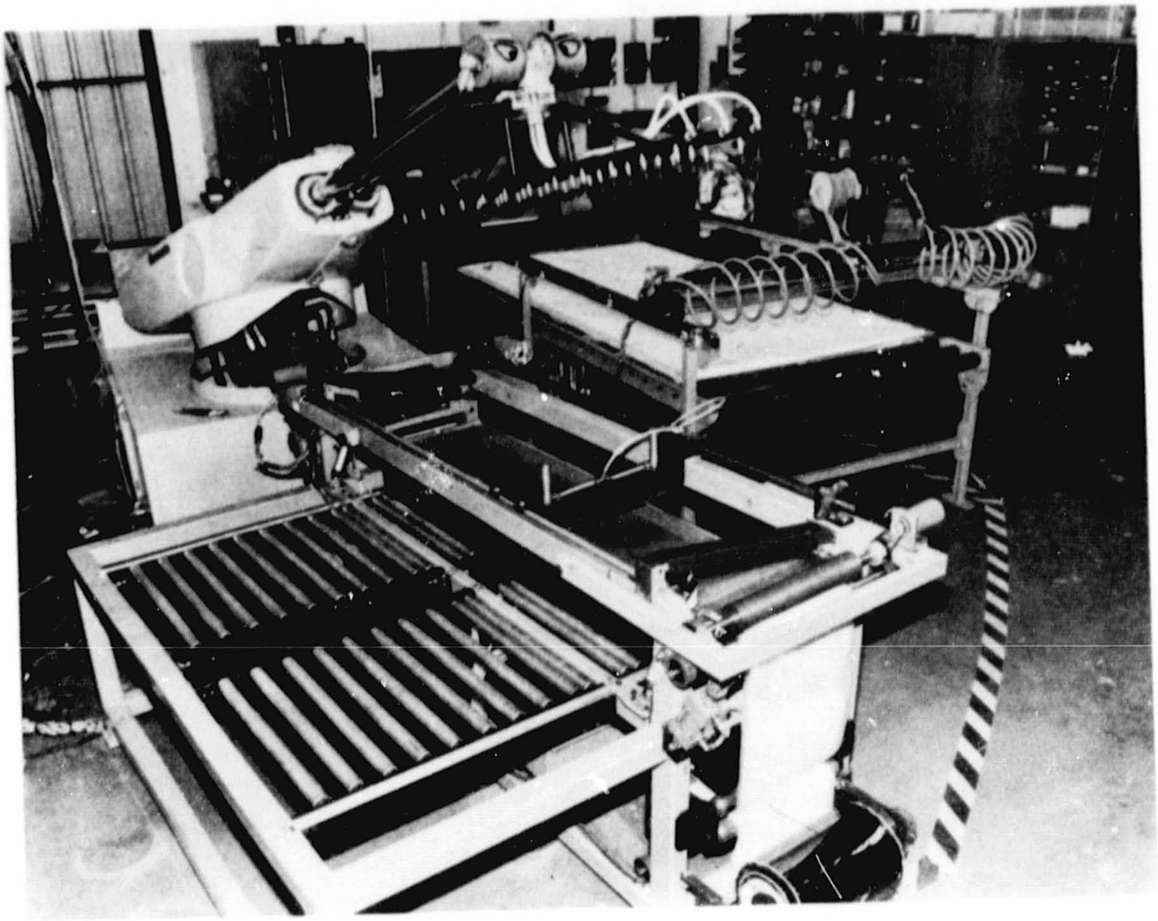
ASSEMBLY

TRACOR MBA
(Poster)

Automated Cell Stringing System



Automated Module Lamination System



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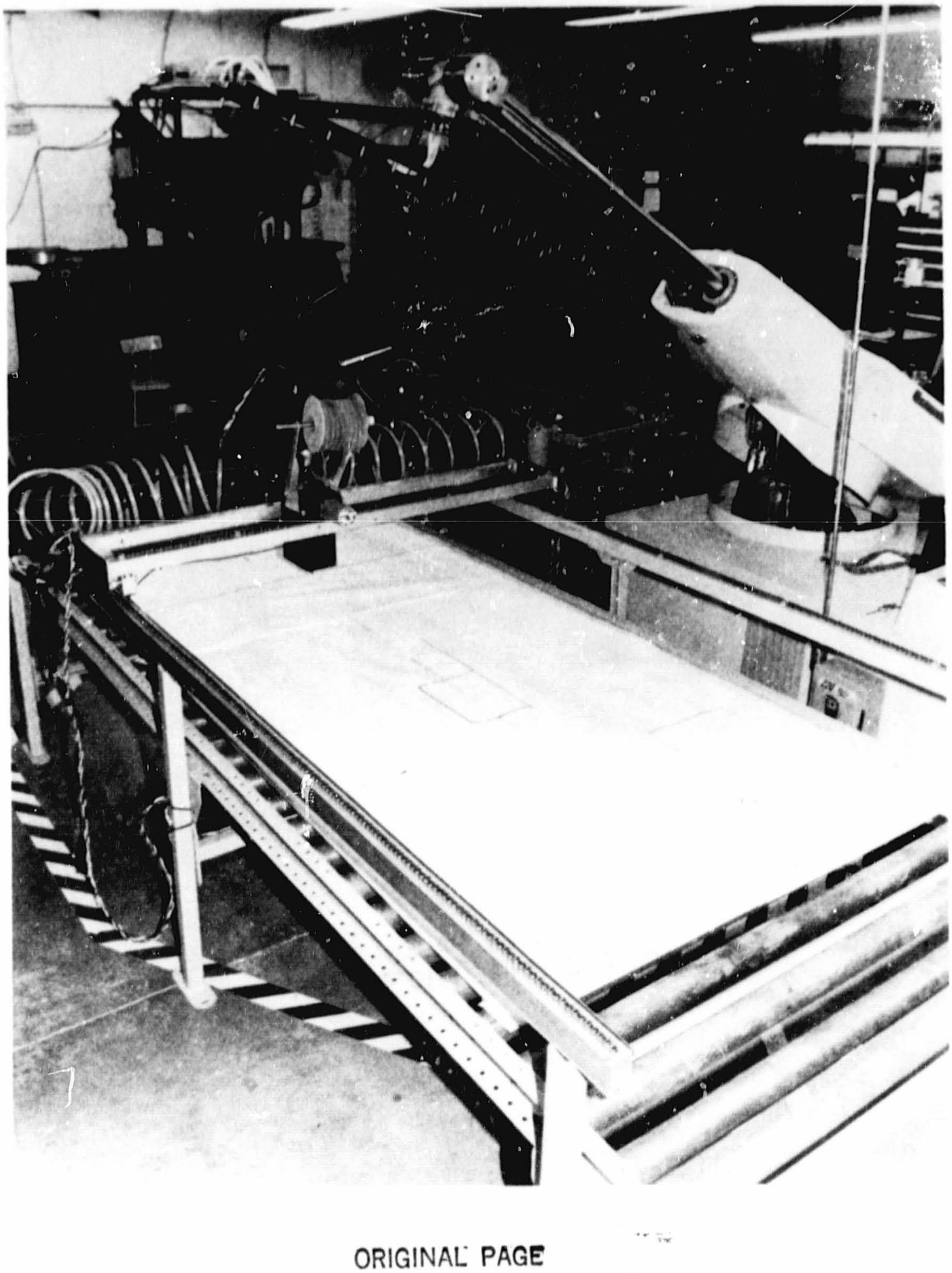
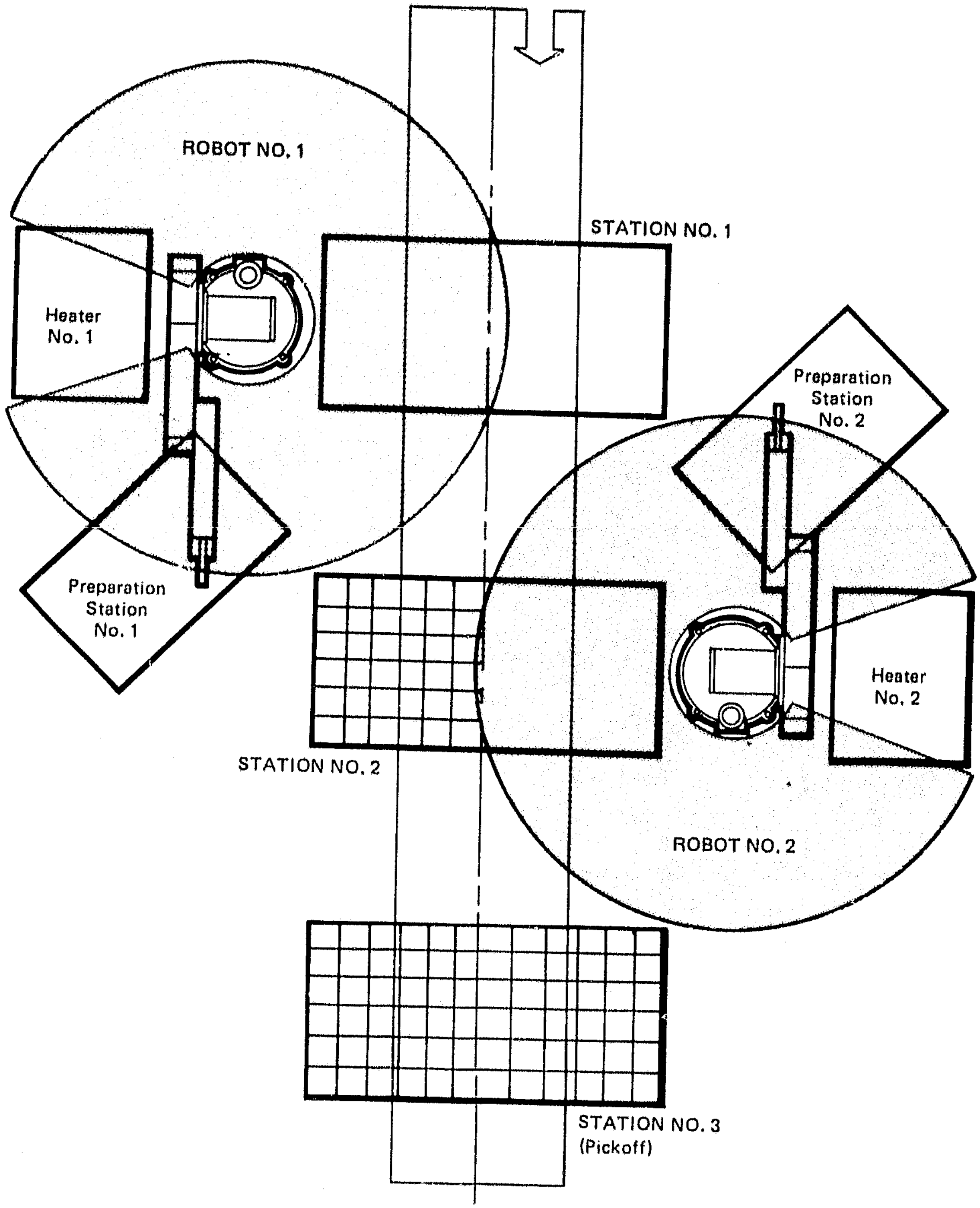
Automated Edge Sealing and Framing



Solar Module Assembly System



PROCESSING EXPERIMENTS ON NON–CZOCHRALSKI SILICON SHEET

MOTOROLA INC.

Major Areas of Investigation

1. PROCESS TECHNOLOGY
   - SUBSTRATE SURFACE PREPARATION
     - SURFACE ETCHING
     - SURFACE TEXTURING
   - SUBSTRATE DRYING
   - HANDLING RECTANGULAR SHAPES
2. CELL DESIGN
   - METALLIZATION PATTERN OPTIMIZATION FOR RECTANGULAR CELLS
3. METALLIZATION
   - PLATED METALLIZATION ADVANCEMENTS
   - THERMAL STRESS STUDIES
4. COST ANALYSIS
   - DOCUMENTATION OF MOTOROLA APPROACH AND COMPARISON WITH SAMIS

Process Technology: Baseline Process Sequence

1. BLANKET PHOSPHORUS DIFFUSION, PH_3 AT 900°C.
2. MESA JUNCTION ETCH, PHOTORESIST WITH A PLASMA ETCH FOR SILICON.
3. SILICON NITRIDE COAT, LPCVD Si_3N_4 AT 780°C.
4. OHMIC PATTERN, PLASMA ETCH NITRIDE.
5. METAL PLATE, NICKEL-COPPER OR PALLADIUM-NICKEL-COPPER.

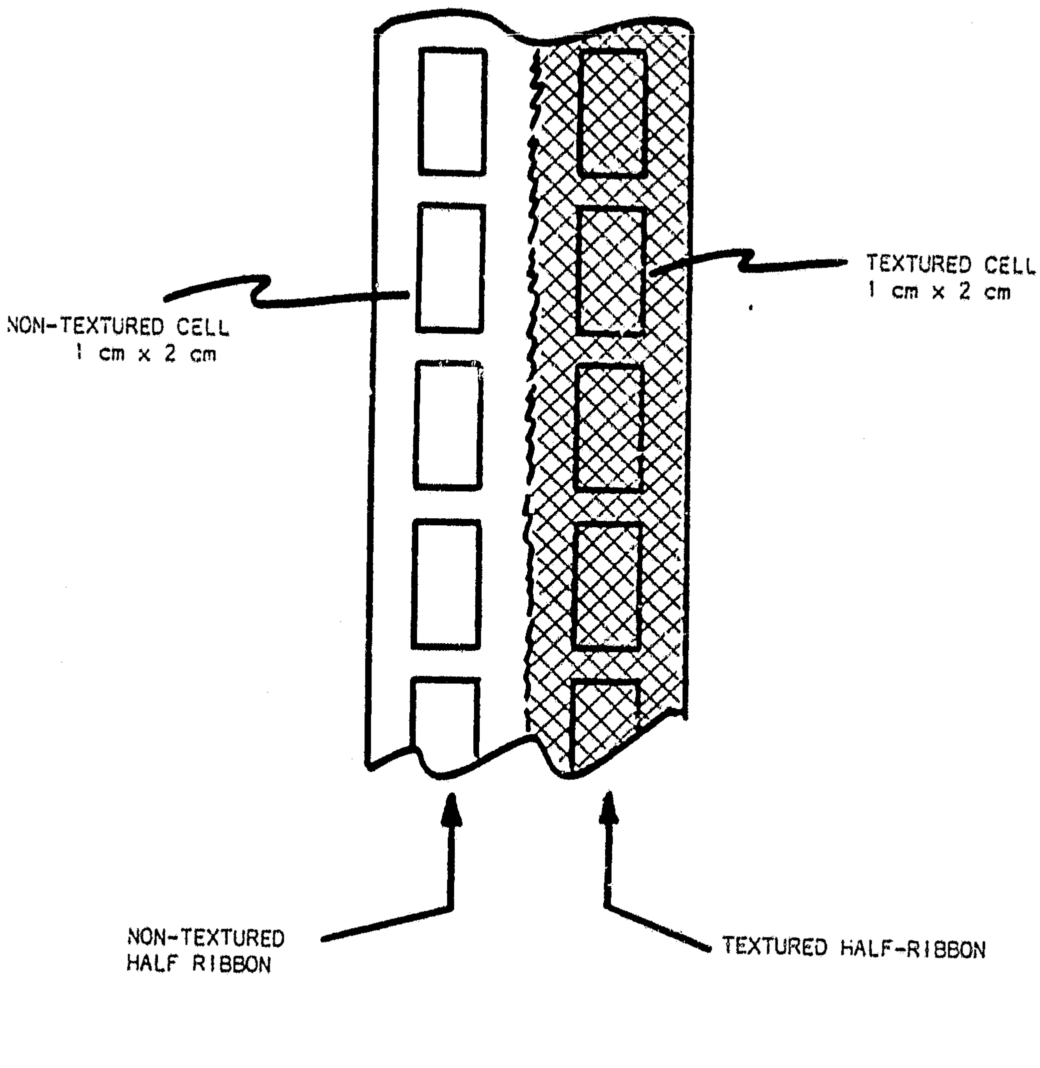
Surface Preparation Experiment

1. DESIRED STRUCTURE: SIDE-BY-SIDE COMPARISON OF TEXTURED AND NON-TEXTURED (FRONT SURFACE) CELLS.

2. PROCEDURE: USE SILICON NITRIDE COATING TO MASK TEXTURED SURFACE PREPARATION ON ENTIRE BACK SIDE AND HALF OF FRONT SIDE (LENGTHWISE) FOR 10 RIBBON SAMPLES.

3. SOLAR CELL STRUCTURE: FORM PAIRS OF SIDE-BY-SIDE 1 CM BY 2 CM SOLAR CELLS, ONE CELL OF THE PAIR ON TEXTURED SIDE AND THE OTHER ON SMOOTH SIDE OF THE RIBBON. (USE BASELINE PROCESS.)

Substrates Used for Texture Etch and Surface Etch Studies



Results

1. 10 RIBBONS PROCESSED, UP TO 11 CELL PAIRS PER RIBBON.
2. 48 PAIRS USED FOR ANALYSIS.
3. 32 PAIRS INDICATED IMPROVEMENT IN SHORT CIRCUIT CURRENT, I_{SC}, WITH TEXTURING.
   AVERAGE I_{SC} INCREASE 2.1 MA OR 4.3%.
4. 15 PAIRS INDICATED DECREASE IN I_{SC} WITH TEXTURING.
   AVERAGE I_{SC} DECREASE 1.6 MA OR 3.2%.
5. TOTAL AVERAGE INCREASE WITH TEXTURING (FOR ALL 48) WAS 0.9 MA OR 1.9%.

Cast Polysilicon Substrates

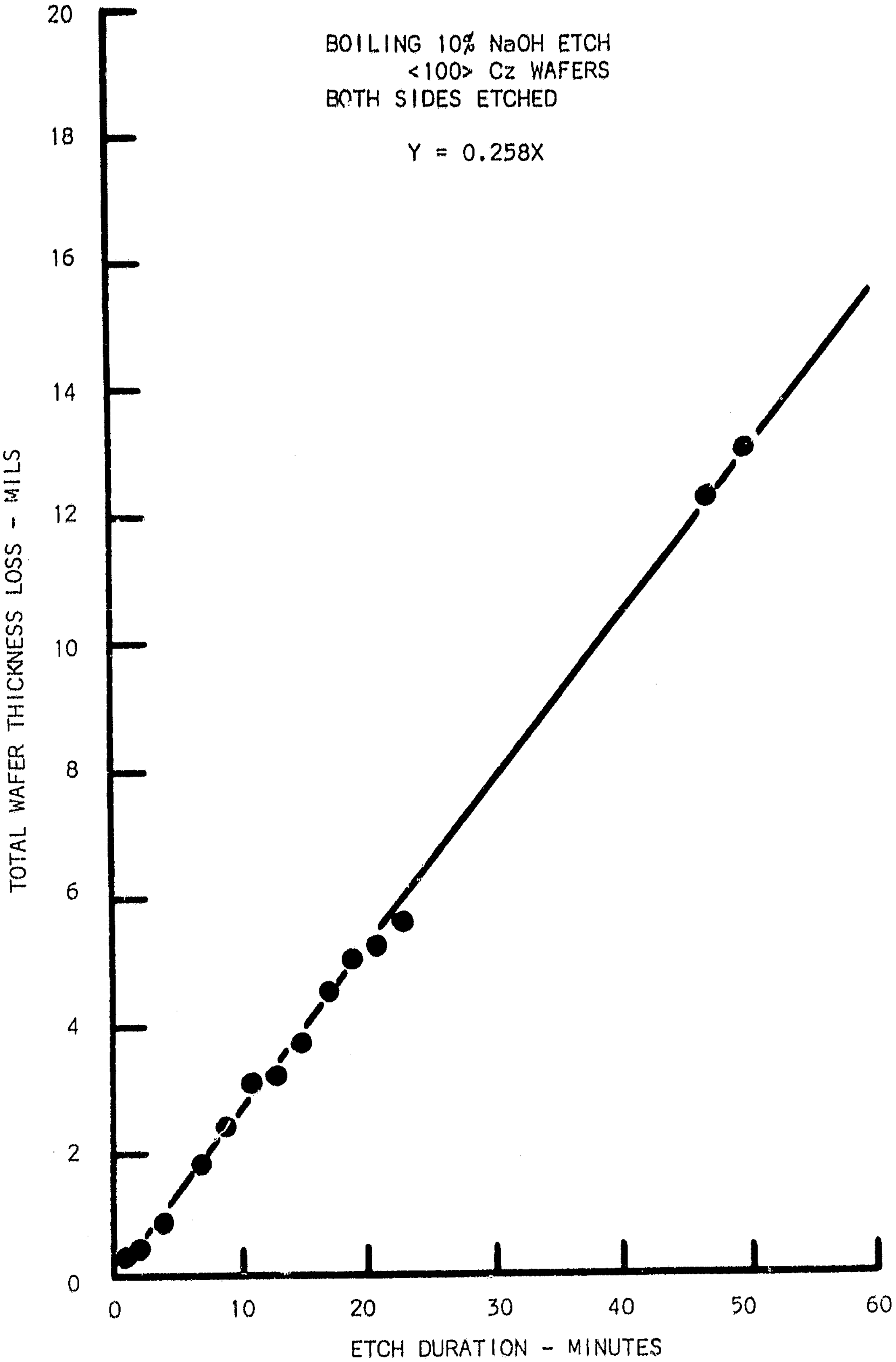
	TEXTURED I_{SC} (MA)	NON-TEXTURED I_{SC} (MA)	INCREASE DUE TO TEXTURE
AVERAGE	52.4MA	50.8MA	1.6MA
STD. DEV.	1.6MA	1.1MA	1.4MA
% STD. DEV.	3.0%	2.2%	

BASED ON 27 CELL PAIRS

Surface Etching:
10% by Weight NaOH Solution Boiling at 102°C

ETCH RATE OBSERVATIONS (THICKNESS LOSS):

<100> CZ WAFERS	0.26	MILS/MINUTE
WACKER-SILSO POLY	0.30	MILS/MINUTE
MOTOROLA RTR	0.40-0.55	MILS/MINUTE



REDUCTION OF THICKNESS FOR BARE SILICON WAFERS IN CAUSTIC ETCH (BOTH SIDES ETCHED).

Metallization: Thermal Stress Studies

NICKEL CONTACT TIME-TEMPERATURE
SINTER MATRIX FOR VARIOUS
SUBSTRATE MATERIALS.

TEMPERATURE (°C)	TIME (min)	SUBSTRATE Cz	RTR	WEB	POLY
250	15	X			
250	30	X	X	X	X
250	60	X	X	X	X
250	120	X			
300	15	X			
300	30	X	X	X	X
300	60	X	X	X	X
300	120	X			
350	30	X	X	X	X
350	60	X	X	X	X
400	15	X	X	X	X

Each X designates a test sample.

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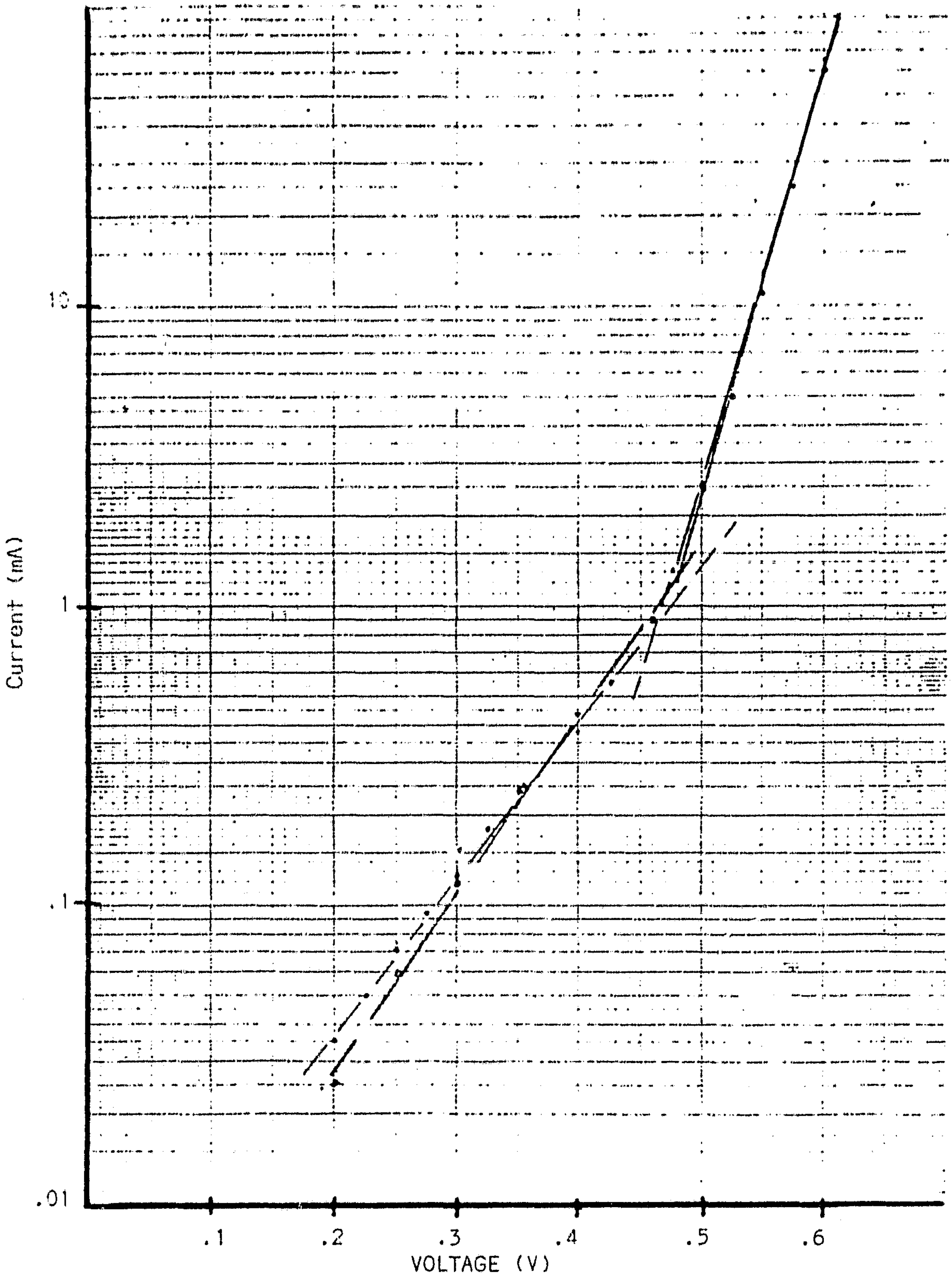

Nickel plated and sintered diode, <100> Cz substrate, 250°C for 15 min., 1.9 cm^2 junction area.

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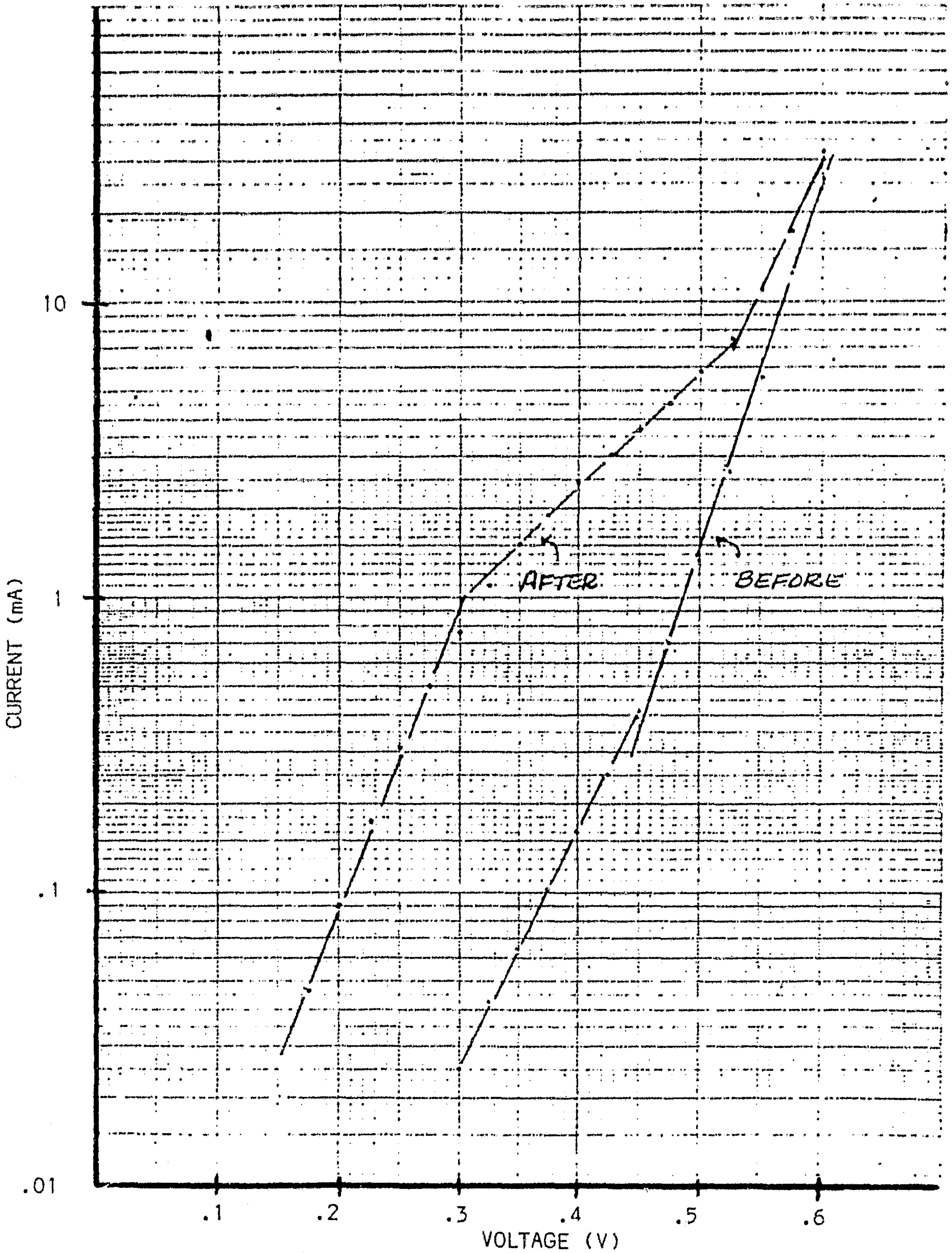


Nickel plated and sintered diode, <100> Cz substrate, 400°C for 15 min., 1.2 cm^2. junction area.

```
          #01 RTRPM1
SUBSTRATE
W0=5.050cm                    D=1.480cm
H=6.533E-004 SQA/W          E0=0.150
R1= 30 Ω/sq
COLLECTOR
R0=5.000E-006 Ω-cmH          N=1.000
BUSS
M=1                          W3=0.102cm
R3=1.700E-004 Ω/sq
MODIFY DATA (Y/N)?
```

```
#01    RTRPM1   OPTIMUM LINEWIDTH
LINEWIDTH    1.36 mils
PERIOD      68.24 mils

LOSS OF EFFICIENCY            0.814%
LOSS OF FILL FACTOR           0.015
SHADOW LOSS OF INPUT          3.971%
COLL        1.959%
BUSS        2.012%

OHMIC EFFICIENCY LOSS         0.219%
SURF         .071%
COLL         .142%
BUSS         .006%
SHADOW EFFICIENCY LOSS        0.596%
COLL         .294%
BUSS         .302%
```

```
#01    RTRPM1     GIVEN LINEWIDTH
LINEWIDTH     3.00 mils
PERIOD      107.83 mils

LOSS OF EFFICIENCY            0.935%
LOSS OF FILL FACTOR           0.015
SHADOW LOSS OF INPUT          4.738%
COLL        2.726%
BUSS        2.012%

OHMIC EFFICIENCY LOSS         0.224%
SURF         .173%
COLL         .046%
BUSS         .006%
SHADOW EFFICIENCY LOSS        0.711%
COLL         .409%
BUSS         .302%
```

```
#01    RTRPM1     GIVEN LINEWIDTH
LINEWIDTH     6.00 mils
PERIOD      141.54 mils

LOSS OF EFFICIENCY            1.230%
LOSS OF FILL FACTOR           0.020
SHADOW LOSS OF INPUT          6.166%
COLL        4.154%
BUSS        2.012%

OHMIC EFFICIENCY LOSS         0.305%
SURF         .285%
COLL         .015%
BUSS         .006%
SHADOW EFFICIENCY LOSS        0.925%
COLL         .623%
BUSS         .302%
```

NICKEL–COPPER METALLIZATION PROCESS

PHOTOWATT INTERNATIONAL, INC.

Goals of the Contract

- TO DEVELOP A RELIABLE METALLIZATION WHICH:
  - -- USES NICKEL PASTE PRINTED OVER (Si_3N_4) AR COATING
  - -- WHEN SINTERED PENETRATES THROUGH Si_3N_4 AND BONDS TO SILICON
  - -- USES BRUSH PLATING OF COPPER FOR ADDITIONAL CONDUCTIVITY
  - -- PRODUCES 4" DIAMETER CELLS OF EFFICIENCY IN EXCESS OF 10% UNDER AM1 28°C
  - -- HAS PULL STRENGTH WITH 5 MM WIDE STRAP OF > 2 LBS WHEN PULLED 90° TO SURFACE
- TO PROVIDE COST DATA ON THE ABOVE SYSTEM

Proposed Cell Processing Sequence

AS-CUT WAFERS

ETCH REMOVAL

N^+ JUNCTION FORMATION

Si_3N_4 DEPOSITION BY LPCVD TECHNIQUE

ALUMINUM BSF FORMATION

PRINT NICKEL OVER Si_3N_4

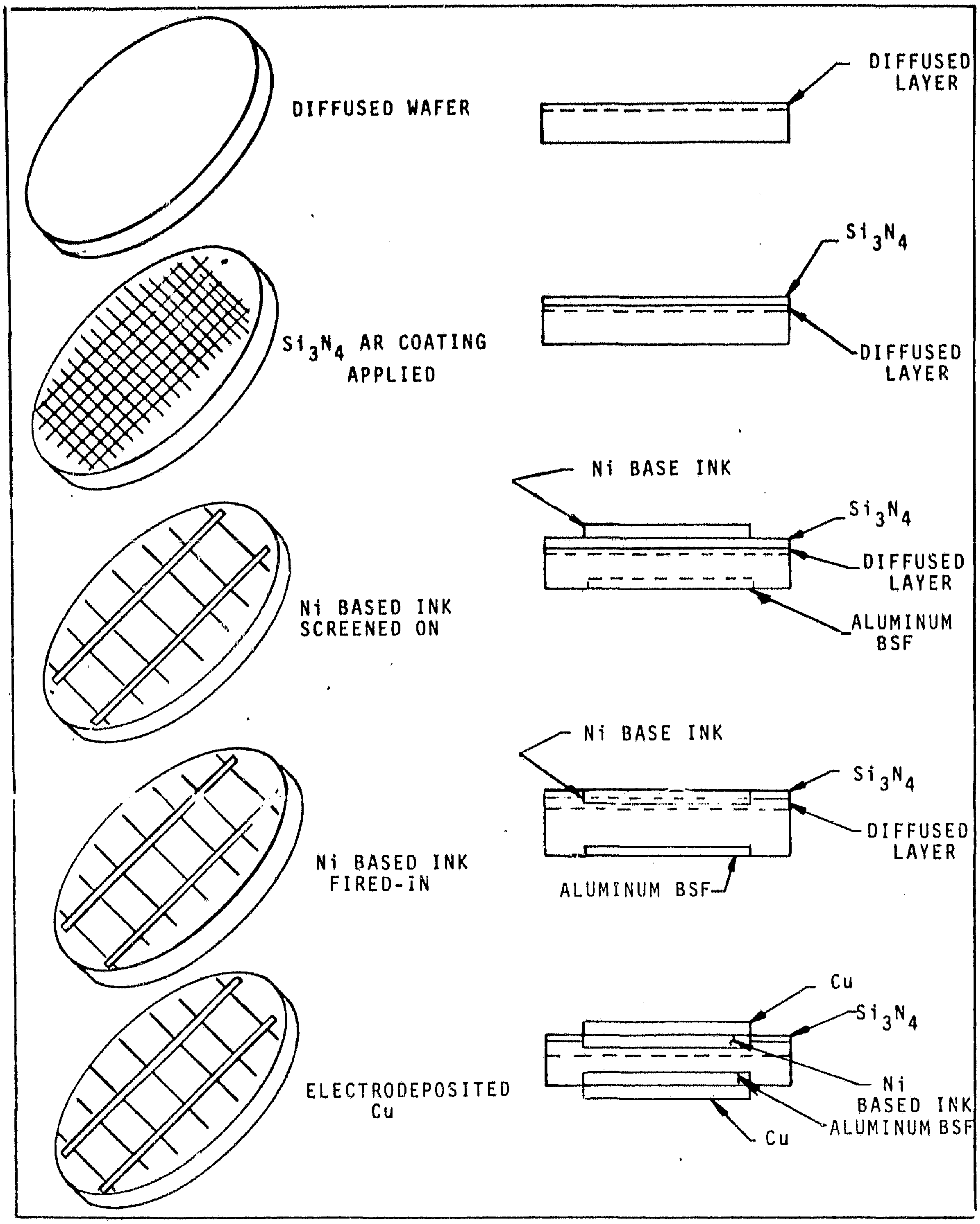
DRIVE-IN

ELECTROPLATE COPPER FRONT & BACK

EDGE JUNCTION SEPARATION

SOLDER DIP

TEST


DIFFUSED WAFER
DIFFUSED LAYER
Si_3N_4 AR COATING APPLIED
Si_3N_4
DIFFUSED LAYER
Ni BASE INK
Ni BASED INK SCREENED ON
Si_3N_4
DIFFUSED LAYER
ALUMINUM BSF
Ni BASE INK
Ni BASED INK FIRED-IN
Si_3N_4
DIFFUSED LAYER
ALUMINUM BSF
ELECTRODEPOSITED Cu
Cu
Si_3N_4
Ni BASED INK
ALUMINUM BSF
Cu

Present Status of Contracts

SUBCONTRACTS NEGOTIATED

- -- NICKEL PASTE DEVELOPMENT - ELECTRO-SCIENCE LAB, PENNSAUKEN, NJ
- -- BRUSH COPPER PLATING - VANGUARD PACIFIC, SANTA MONICA, CA

SAMPLES OF CELLS

- -- WITH VARIOUS NITRIDE THICKNESS PROVIDED TO ESL LABS
- -- FOR REVERSE ETCHING OPTMIZATION PROVIDED TO VANGUARD PACIFIC
- -- ETCHING CHARACTERISTICS ON NICKEL PASTE BEING EVALUATED
- -- COPPER SOLUTION (PH) COMPATIBILITY WITH NICKEL PASTE UNDER EVALUATION

Advantages of the Process

- USES LOW COST NICKEL PASTE
- ELIMINATES NEED FOR MASKING AND ETCHING--HENCE LABOR COSTS
- UTILIZES STATE-OF-THE-ART EQUIPMENT FOR HIGH THROUGHPUT
- UTILIZES CONTINUOUS BRUSH PLATING OF COPPER INSTEAD OF BATCH PLATING
- OVERALL COST OF PROCESS SEQUENCE IS LOWER, BY A FACTOR OF 3, THAN THE EXISTING ELECTROLESS NICKEL SOLDER PROCESS SEQUENCE

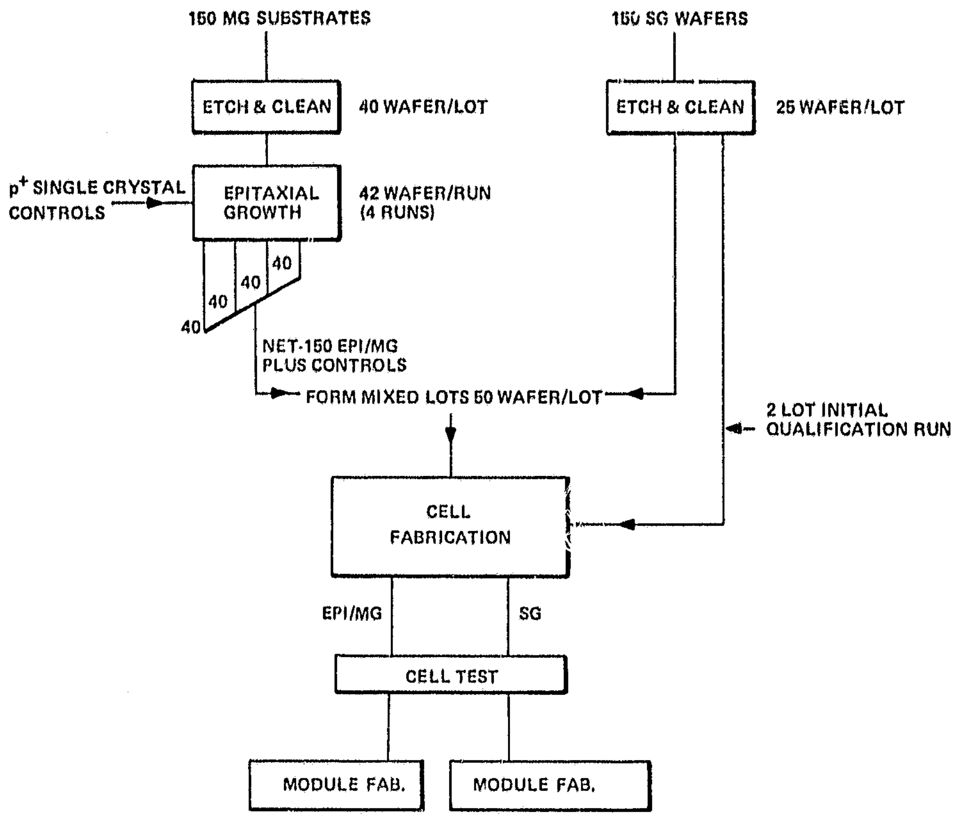
Cellco Added Value (1980 ¢/W)

PROCESS REFERENT	EQUIPMENT COST	FLOOR SPACE	LABOR COST	MATERIAL COST/BY PROD.	UTILITIES COST	TOTAL PROCESS COST
ORGANIC REMOVAL	.0826	.0212	.0918	0.3748 -.0056	.4092	.9741
ETCH	.7392	.0841	.8382	.9316 -.0139	.5785	3.1577
SPRAYJUNC	.3878	.1122	.1886	.3471 -.0138	.2227	1.2446
LPCVDNIT	.9539	.0676	.6841	.4008 -.0166	.0008	2.0907
ALUMINUM BSF	.4091	.1110	.1865	.0014 -.0137	.2203	.9145
LASRIM	.8069	.0776	.8135	0.0 -.0152	.1577	1.8405
TESTCELL	.0845	.0153	.1436	0.0 -.0128	.0132	.2438
TOTAL ELEMENT COST	4.0637	.7537	4.0525	2.7808 -.1297	2.2584	13.7794

EPITAXIAL PROCESS SEQUENCE

RCA CORP.

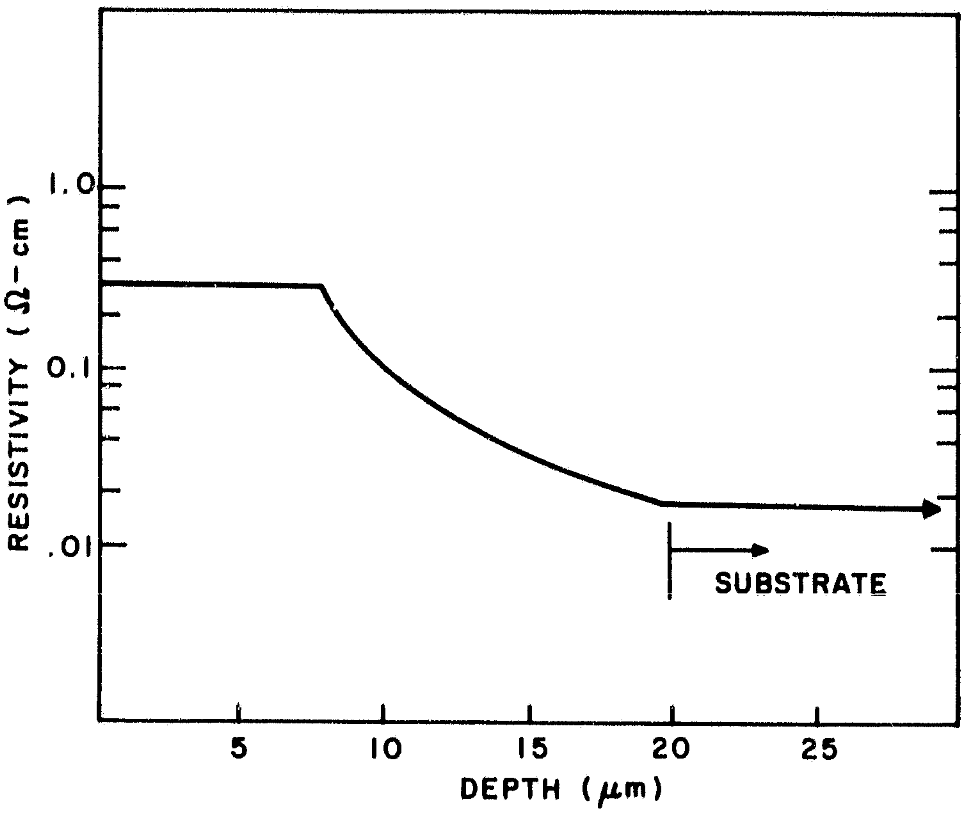
D. Redfield

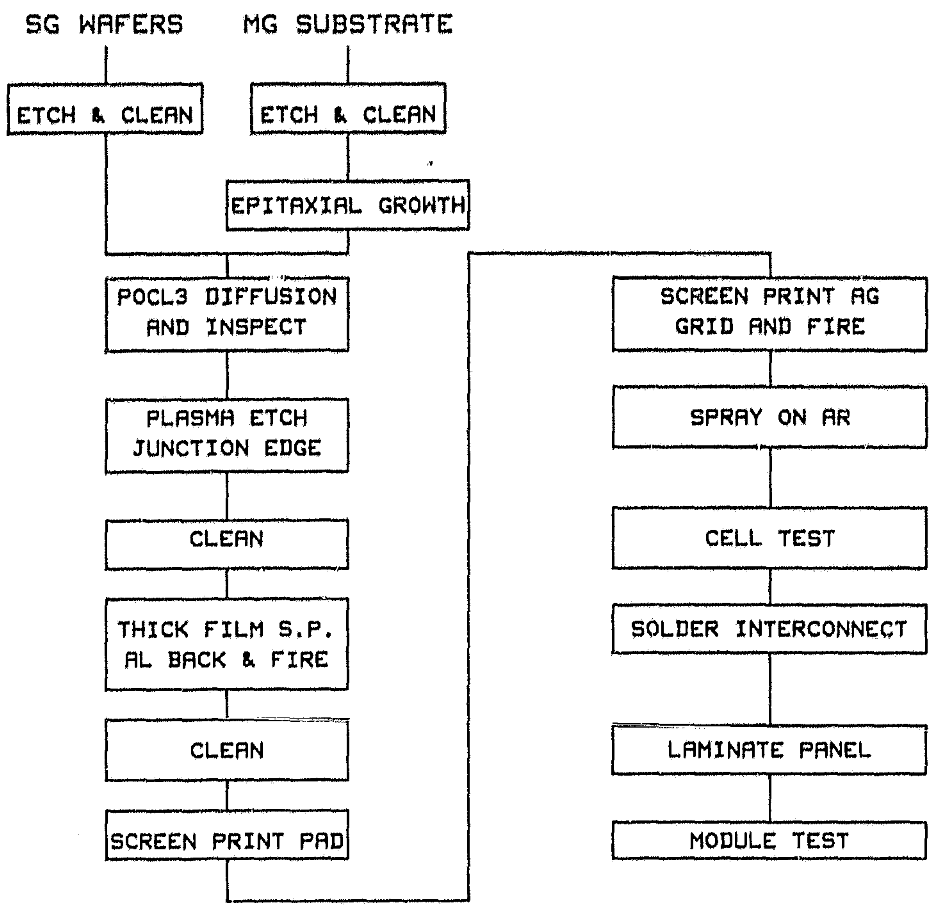


Small-Module Test and Disposition Requirements

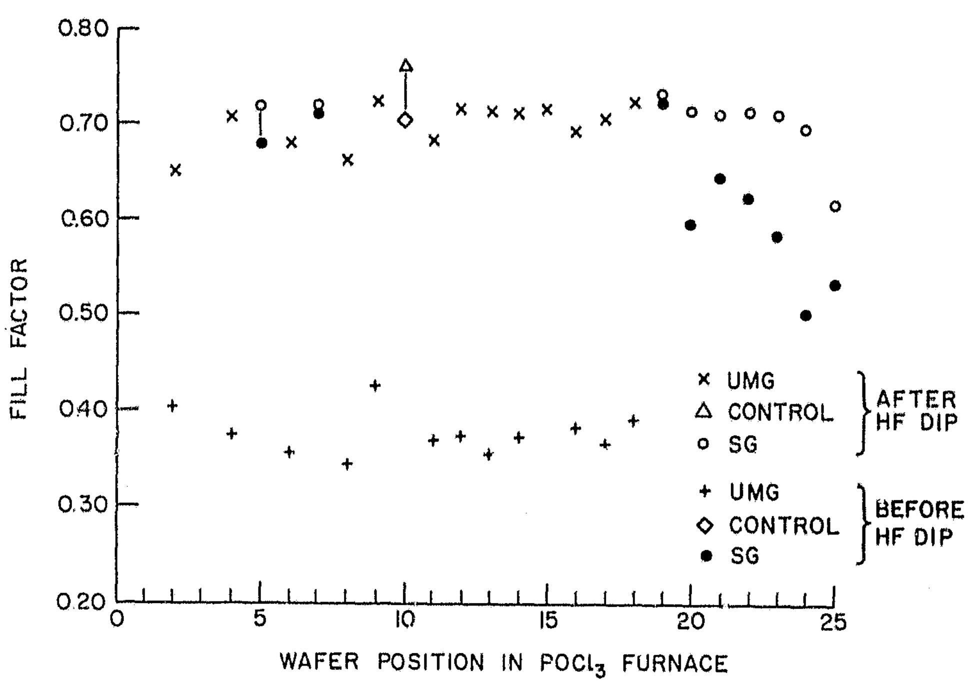
	CONF 1	CONF 2
(1) STARTING Si MATERIAL	SEMICONDUCTOR GRADE WAFERS	ENHANCED METALLURGICAL GRADE WAFERS
(2) CELL SIZE	3.0 in. dia. (OR EQUIV.)	(3.0 in. dia. (OR EQUIV.)
(3) MODULE SIZE	11.64 in. X 15.64 in.	11.64 in. X 15.64 in.
(4) CELLS/MODULE	TBD	TBD
(5) MODULES TO BE TESTED BY CONTRACTOR	7	7
(6) MODULES TO BE SENT TO JPL DIRECTLY WITH ELECTRICAL PERFORMANCE MEASUREMENTS ONLY	7	7

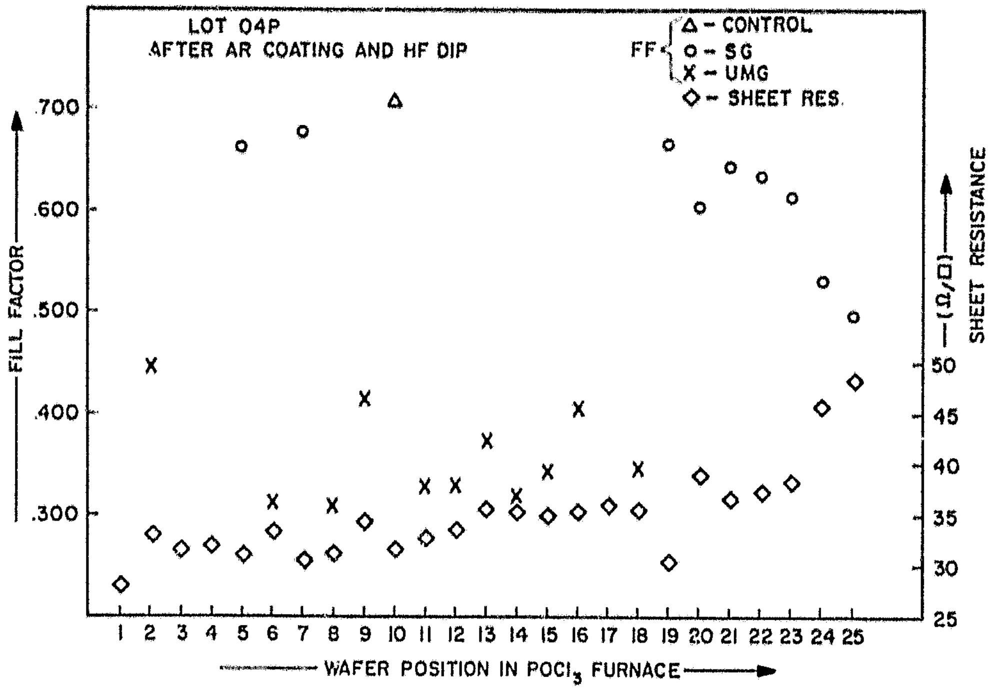
Representative Resistivity Profile of Epitaxial Layer



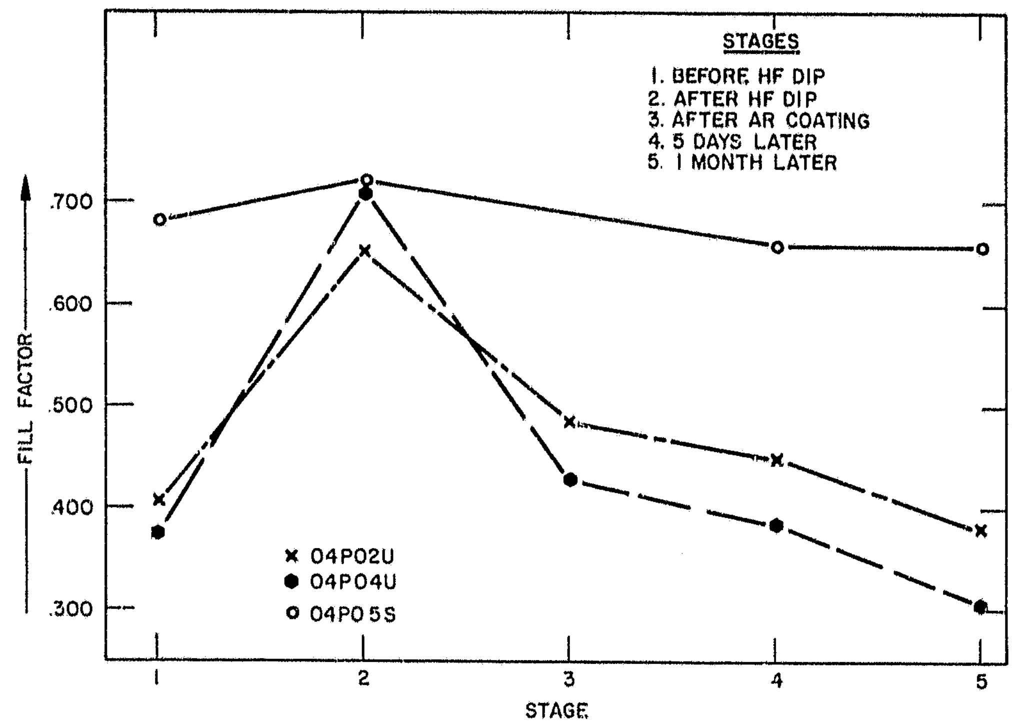


Process Lot 04P





LOT 04P
AFTER AR COATING AND HF DIP
FF
Δ - CONTROL
O - SG
X - UMG
◇ - SHEET RES.
FILL FACTOR
SHEET RESISTANCE
(Ω/□)
.700
.600
.500
.400
.300
50
45
40
35
30
25
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
WAFER POSITION IN POCl$_3$ FURNACE



STAGES
1. BEFORE HF DIP
2. AFTER HF DIP
3. AFTER AR COATING
4. 5 DAYS LATER
5. 1 MONTH LATER
FILL FACTOR
.700
.600
.500
.400
.300
× 04P02U
● 04P04U
○ 04P05S
1
2
3
4
5
STAGE

DEVELOPMENT OF ALL-METAL THICK-FILM COST-EFFECTIVE METALLIZATION SYSTEM

BERND ROSS ASSOCIATES

Bernd Ross

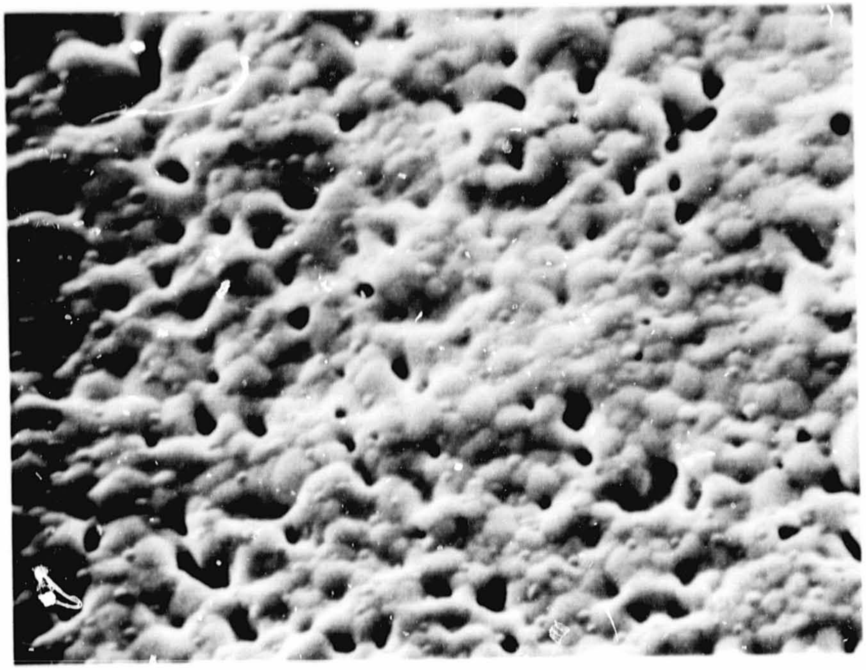
Progress

A COPPER-LEAD SILVER FLUORIDE PASTE GAVE ADHERENT CONTACTS TO SILICON.

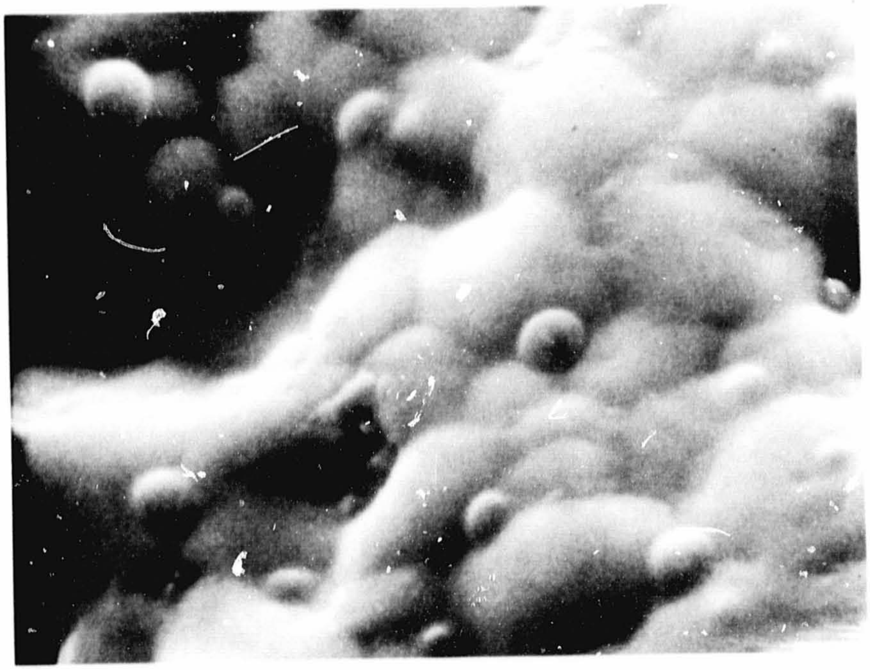
EARLIER SILVER PASTE RESULTS WERE REPRODUCED.

A COPPER-LEAD-CARBON FLUORIDE PASTE GAVE ADHERENT CONTACTS BEFORE AND AFTER DI WATER BOIL TEST.

A SOLAR CELL FABRICATED WITH ABOVE NONOPTIMUM CONTACT GAVE AMI EFFICIENCY OF 7% UNCOATED.



Reproduction of silver electrode with original silver paste S032 with 5 wt.% Pb, 2 wt.% AgF. Print was fired in hydrogen at 550°C for 5 min. Note tightly sintered structure with few open spaces. Cambridge SEM, 1800X.



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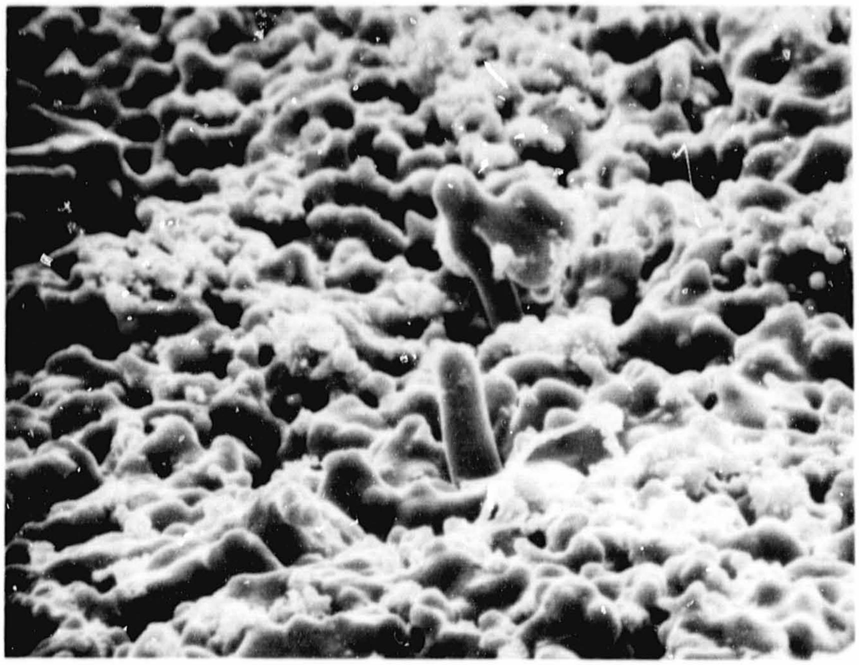
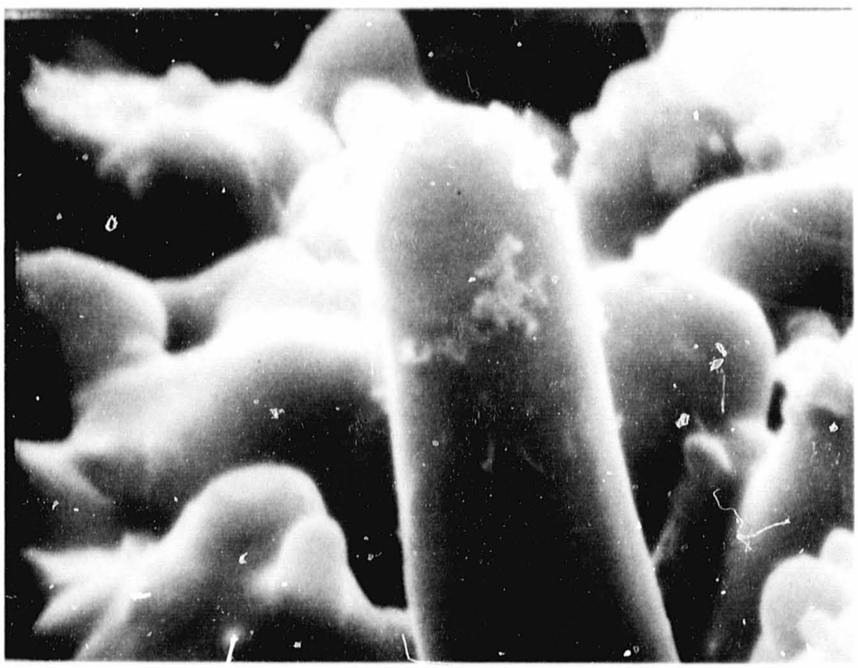
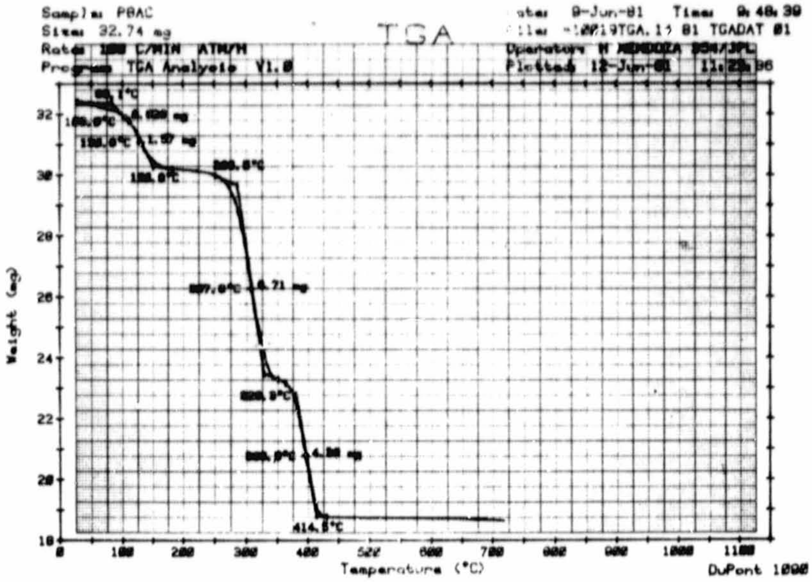


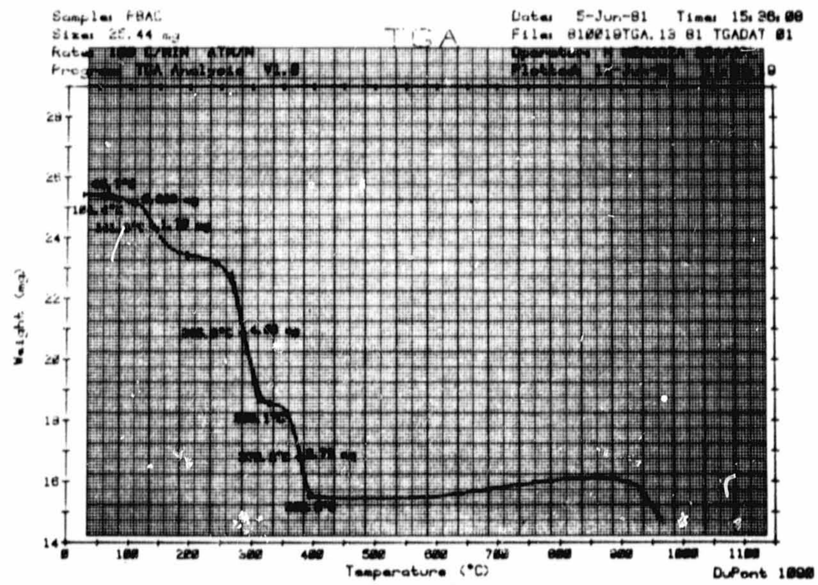
SEM photomicrograph of F17 copper print with 1.2 wt.% AgF fired at 625°C by two-step process. Exposure was done at oblique angle (64°) to bring out needle formations of the Cu-Si eutectic. This electrode passed the Scotch Tape adherence test. 2100X.



Same as above, 10 500X



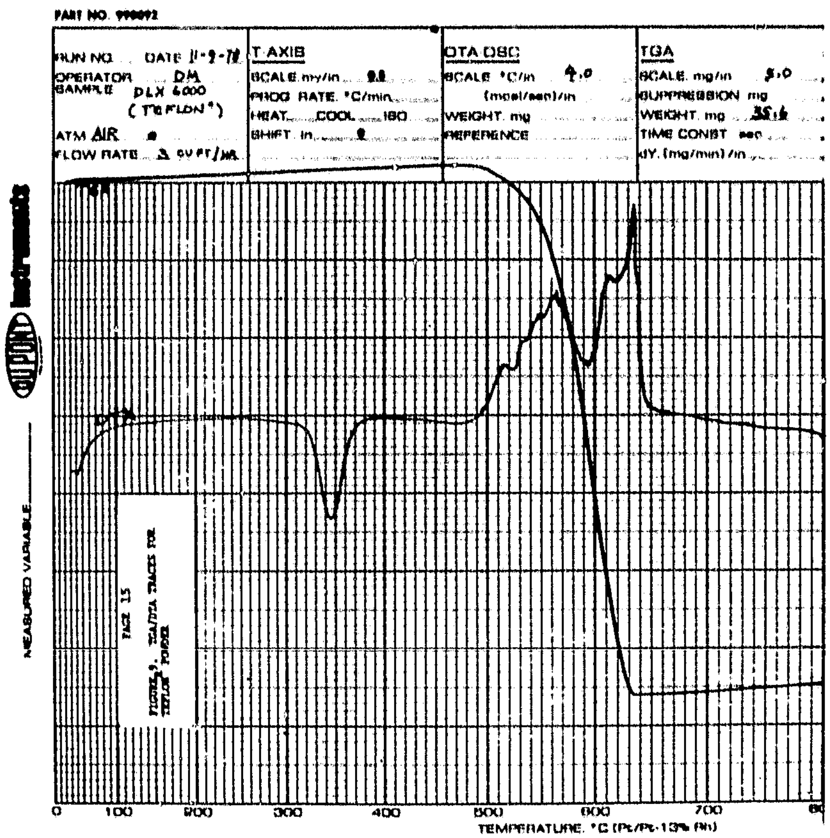
Thermal gravimetric analysis (TGA) curve of lead acetate run in hydrogen (Courtesy Brian Gallagher, JPL).



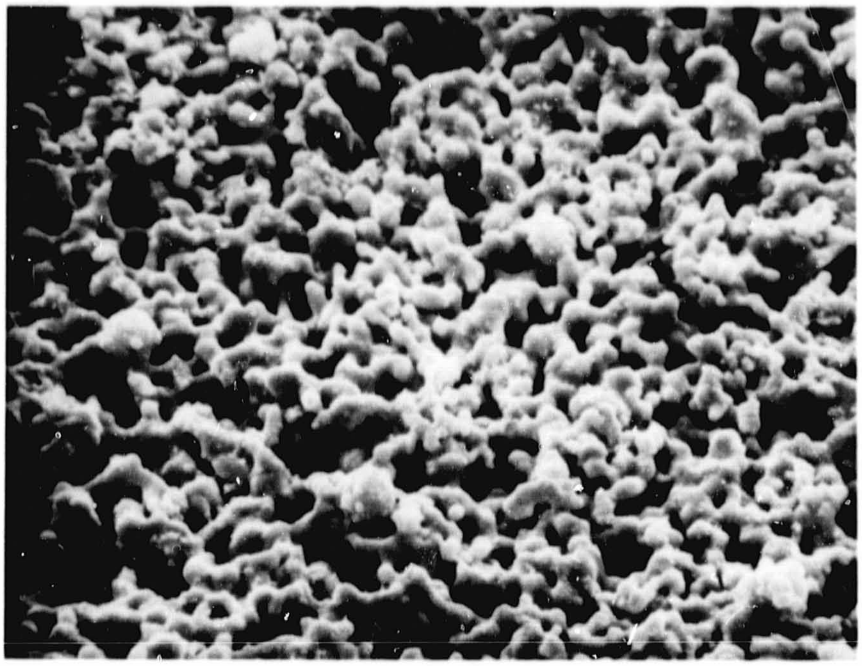
TGA curve of lead acetate run in nitrogen (Courtesy Brian Gallagher, JPL).

PROCESS DEVELOPMENT AREA

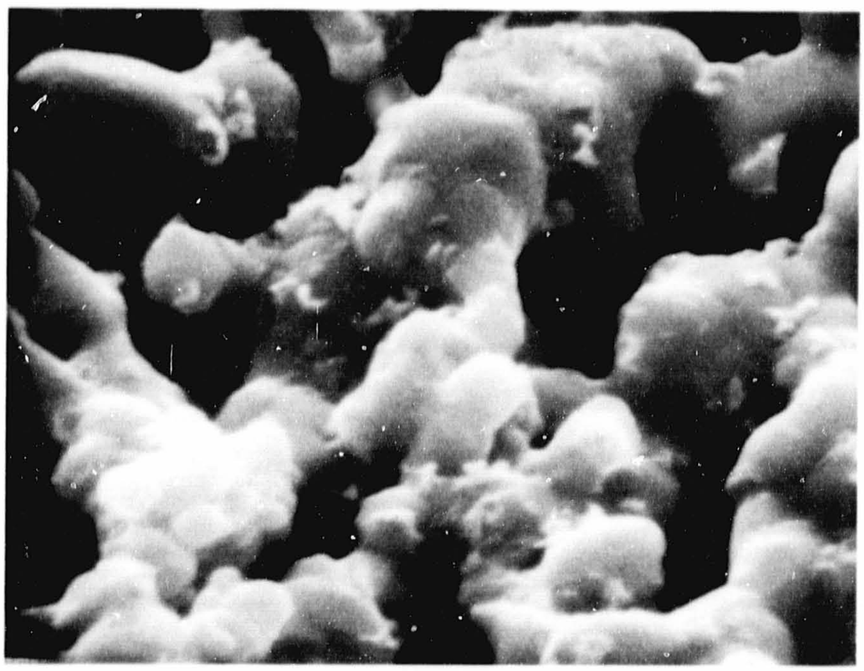
ORIGINAL PAGE IS
OF POOR QUALITY



Thermal gravimetric analysis and differential thermal analysis of carbon fluoride run in air. Runs have been made on several production runs of this material, and in nitrogen and hydrogen atmospheres, with similar results.



SEM photomicrograph of copper paste F13 with 1.1 wt.% carbon flouride and 2.3 wt.% lead acetate, fired at 550°C by the two-step process. This material passed scrape and Scotch Tape tests and DI water boil. Note the relatively open structure, indicative of immature sintering process. Magnification 1800X.



Same as above, 9000X

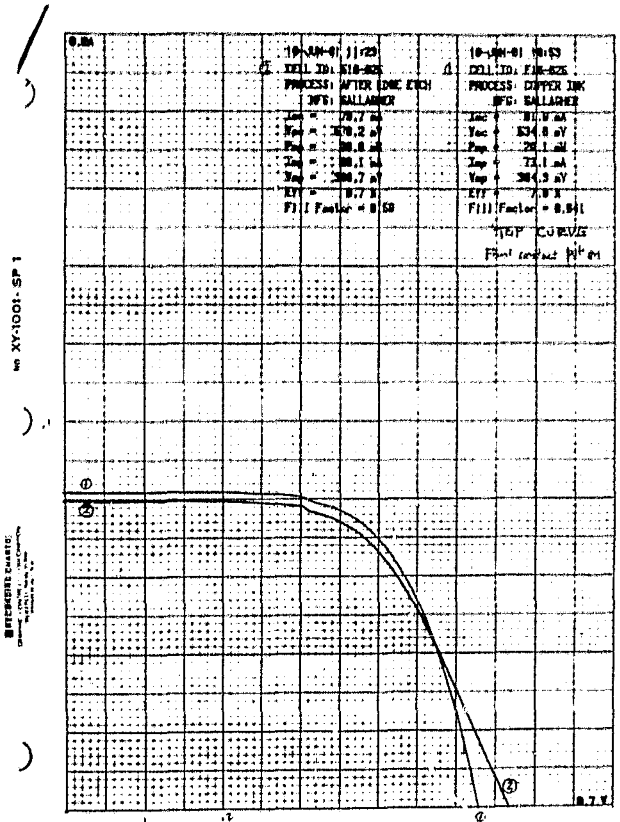


Figure 1.
18

IV curve of 2 x 2 cm solar cell with screened copper back electrode made with paste F16, containing 1.1 wt.% carbon fluoride and 4.5 wt.% lead acetate. Print was fired by two-step process at 625°C. Electrode on cofired pieces did not pass Scotch Tape or scratch tests. Projected AM1 efficiency 10%. Edge etch resulted in curve (2) with improved V_{oc} but increased series resistance. (Courtesy Brian Gallagher, JPL).

Conclusions and Problems

1. AN ECONOMICAL COPPER PASTE EMPLOYING CARBON FLUORIDE POWDER OXIDE SCAVENGER YIELDED GOOD DEVICES AND SHOWS FURTHER PROMISE.

2. PREVIOUS COPPER ELECTRODES USING AGF DID NOT SURVIVE 1 YEAR'S STORAGE.

3. PROBLEMS EXIST WITH REPRODUCIBILITY OF FIRING RESULTS BOTH DURING A SINGLE RUN AND BETWEEN RUNS.

4. COPPER ELECTRODE PASTES WITH SILVER FLUORIDE AS WELL AS CARBON FLUORIDE ADDITIVES HAVE PASSED SCRATCH AND SCOTCH TAPE TESTS, AND SHOWN SOLDERABILITY.

5. A COPPER PASTE WITH CARBON FLUORIDE ADDITIVE PASSED THE SCOTCH TAPE ADHERENCE TEST BEFORE AND AFTER IMMERSION INTO BOILING DI WATER FOR OVER 10 MINUTES.

6. THE PROCESS WINDOW FOR BASE METAL PASTES IS NARROWER THAN THAT FOR SILVER ELECTRODES.

HIGH-RESOLUTION, LOW-COST CONTACT DEVELOPMENT (MIDFILM)

SPECTROLAB, INC.

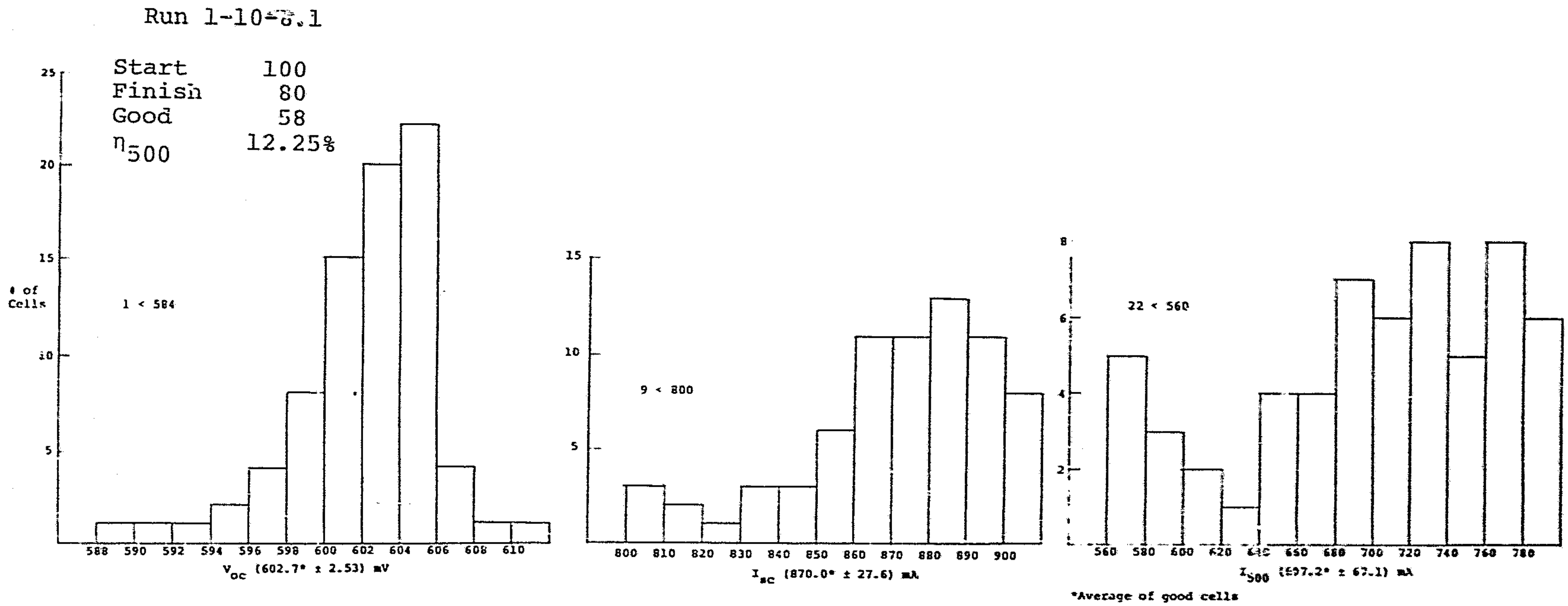
Nick Mardesich

Powder and Resin Recommendations

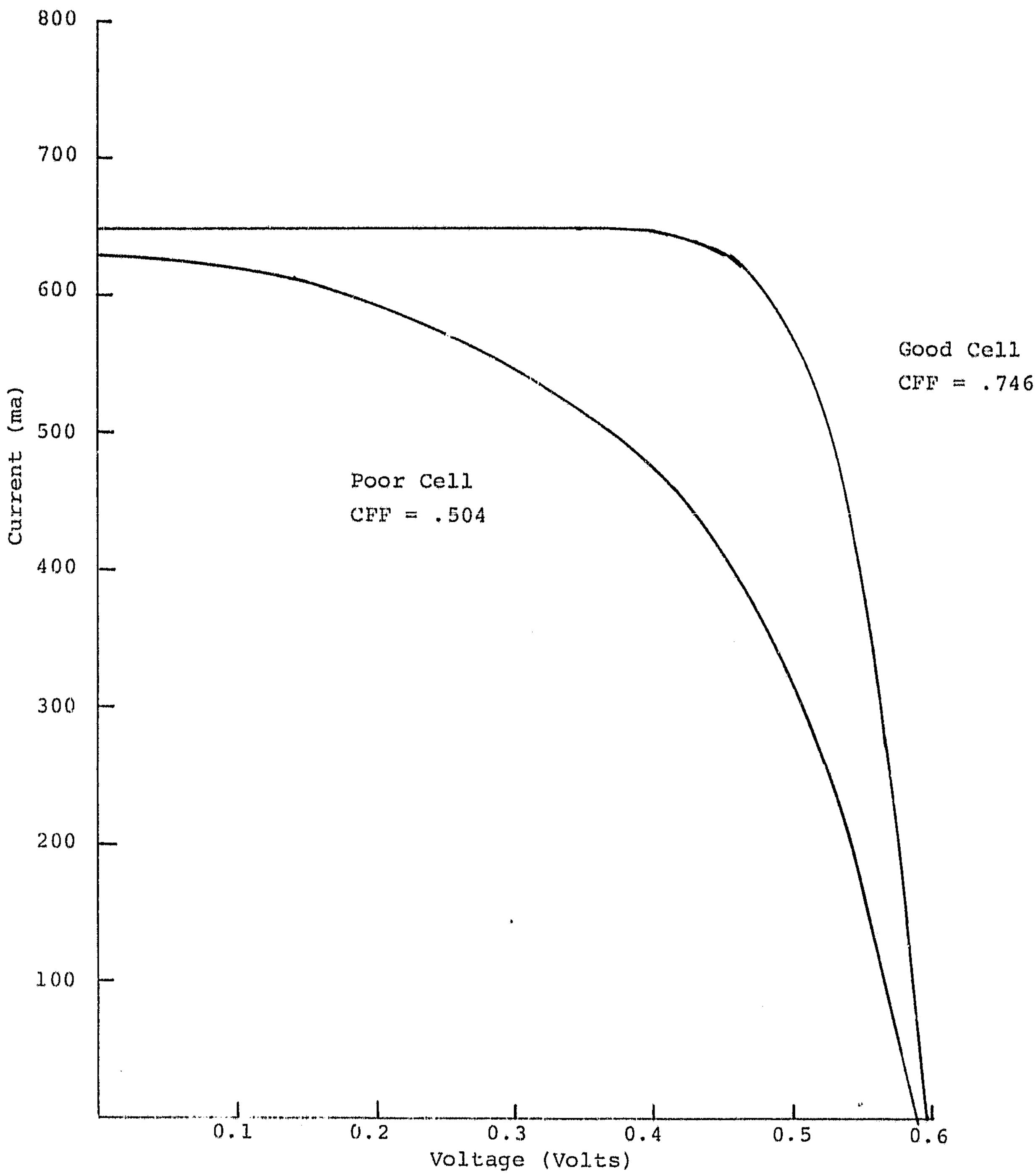
- OPTIMUM SILVER POWDER
  - -- POWDER #3347* (THICK FILM SYSTEMS, INC.)
  - -- LOW SERIES RESISTANCE
  - -- SOLDERABLE
- OPTIMUM RESIN
  - -- MIDFILM RESIN #RC-4933
  - -- NO HUMIDITY SENSITIVITY

*95% TFS SPHERICAL TYPE POWDER
5% 3347 TFS FRIT

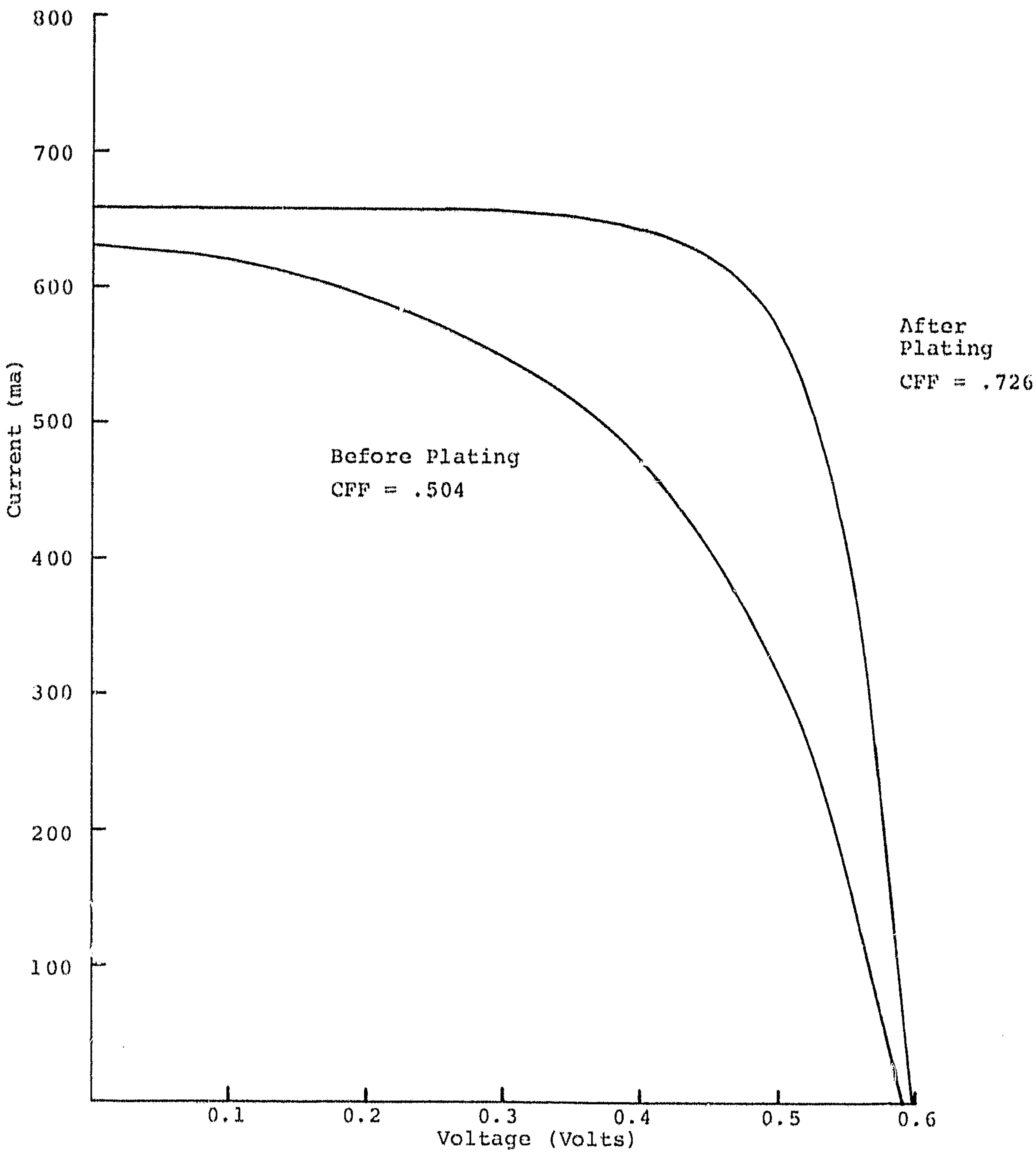
Histograms of Average Production Lot



I-V Characteristics of Good and Poor Midfilm Cell



Effect of Silver on Poor Midfilm Cell



Effect of Conductive AR Coating On Curve Fill Factor of Midfilm Cells

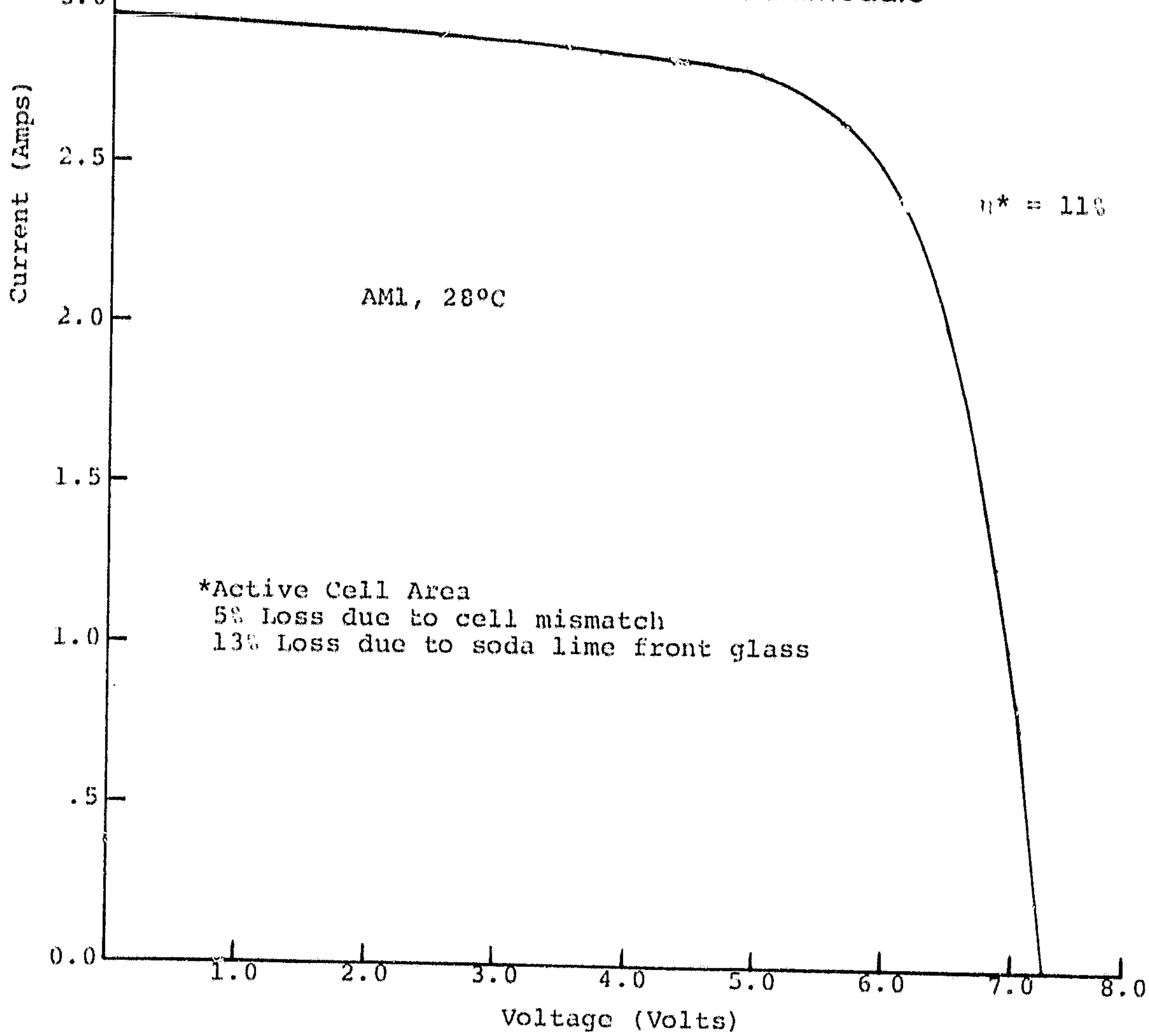
ITO AR COATING (~ 50 Ω/ , 750Å)

CELL #	CFF
B-14	.739
B-15	.741
B-16	.729
B-17	.741
B-18	.742
B-10	.741

SiOx AR COATING (~ 750Å)

CELL #	CFF
B-4	.644
B-6	.491
B-19	.622
B-21	.692
B-23	.521

I-V Characteristics of Midfilm Minimodule



Alternative Materials Composition

POWDER	COMPOSITION
TFS 5514	AIR-FIRING Cu POWDER
TFS 5517	AIR-FIRING Ni POWDER
RH 3659-B	.2 Mo, .8 Sn
RH 3659-C	.195 Mo, .8 Sn, .005 TiH_2
RH 3659-D	.2 MoO_x .8 Sn
RH 3665	.195 MoO_x .8 Sn, .005 TiH_2
RH 3662	.2 W, .8 Sn
RH 3659-A	.85 Mo, .15 Sn
RH 3659-E	.85 Ni, .15 Sn

Firing Parameters of RH 3659-C

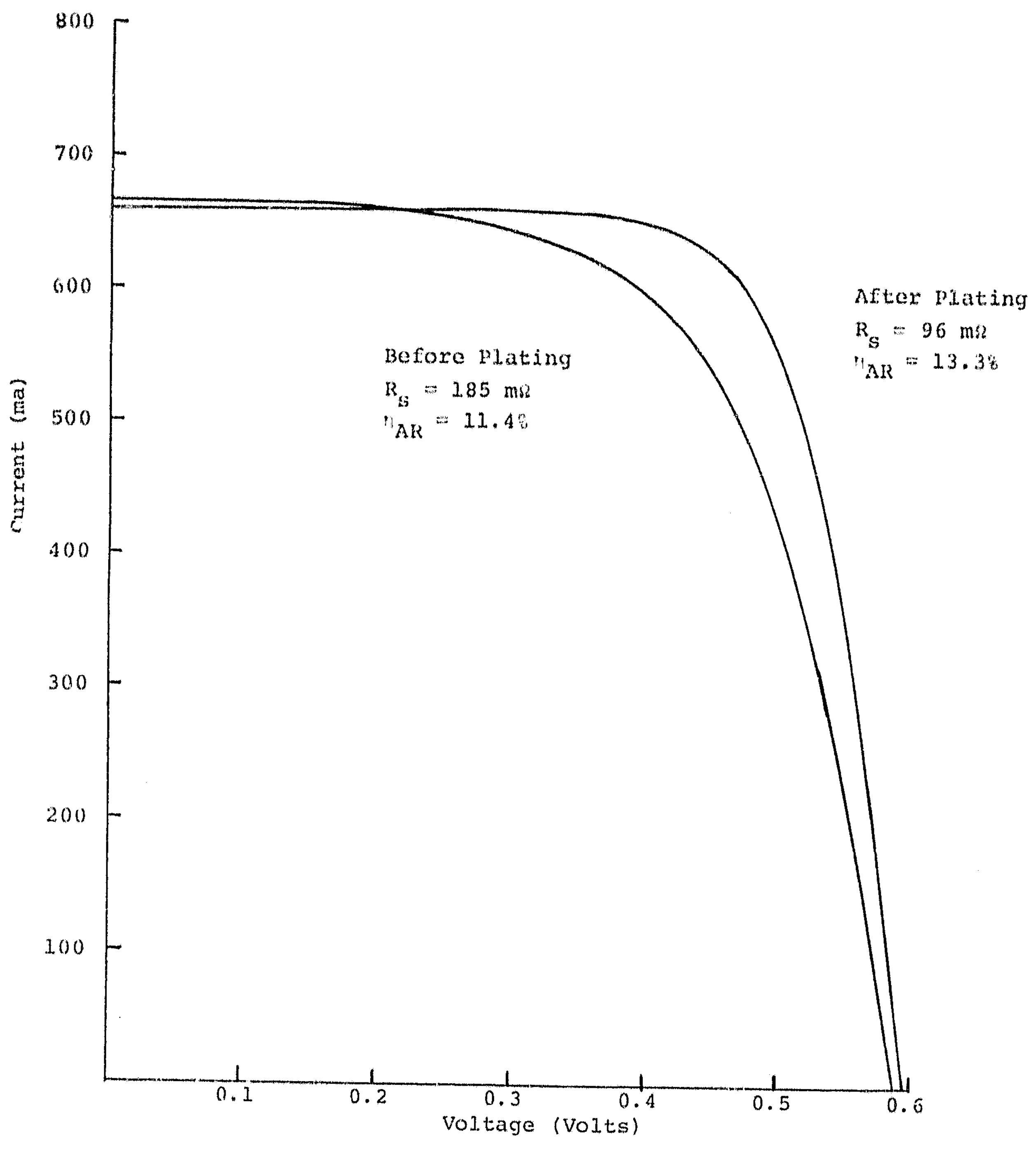
- PRE-FIRE AT 500°C, 30 MIN. IN AIR

  -- REMOVE ORGANICS

- 2 FIRINGS AT 675°C, 36 MIN. IN 95% N_2, 5% H_2

  -- SINTER POWDER

I-V Characteristics of RH 3659-C Midfilm Cell Before and After Silver Plating

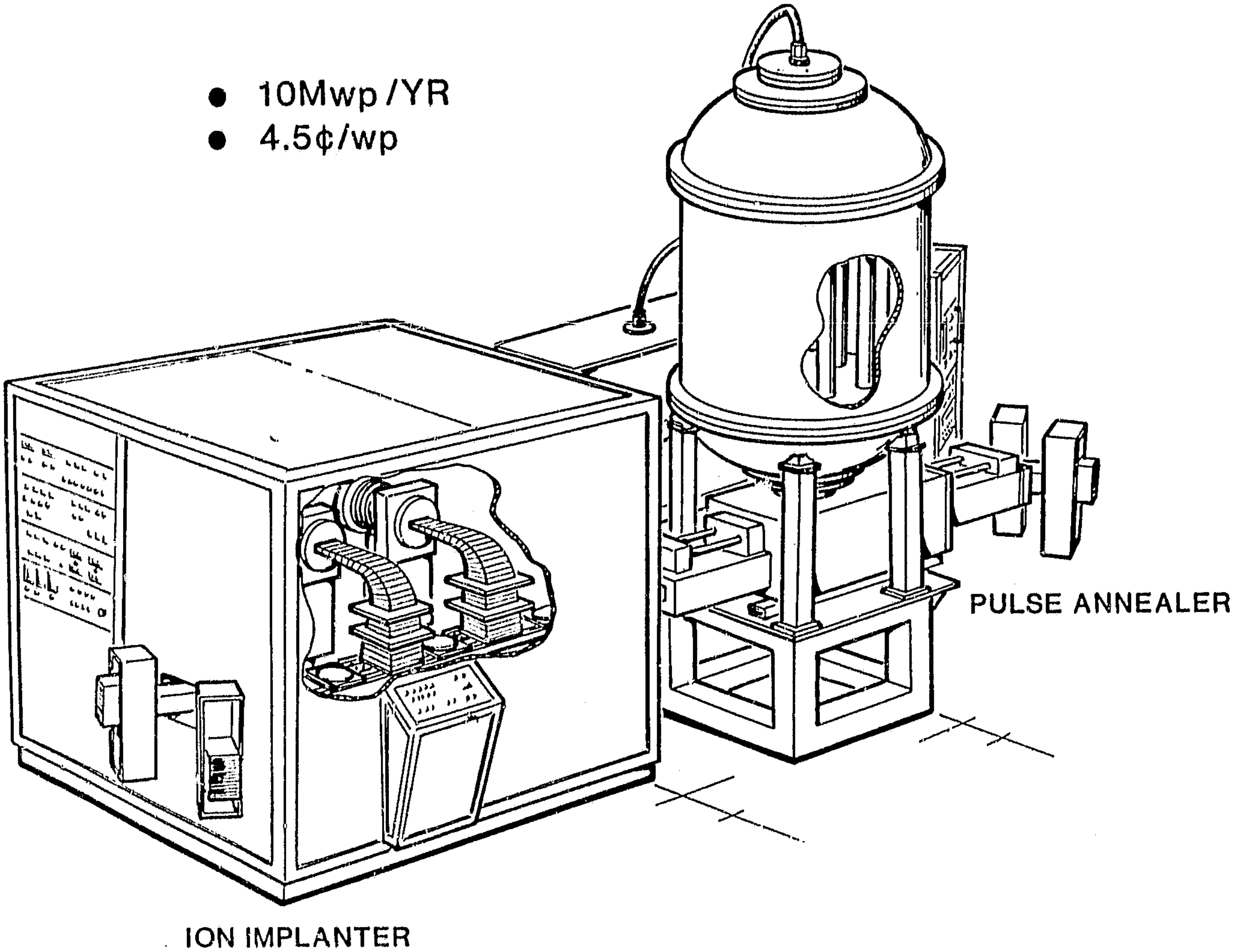


DEVELOPMENT AND FABRICATION OF A SOLAR CELL JUNCTION PROCESSING SYSTEM

SPIRE CORP.

Spire-JPL Junction Processor

- 10Mwp /YR
- 4.5¢/wp

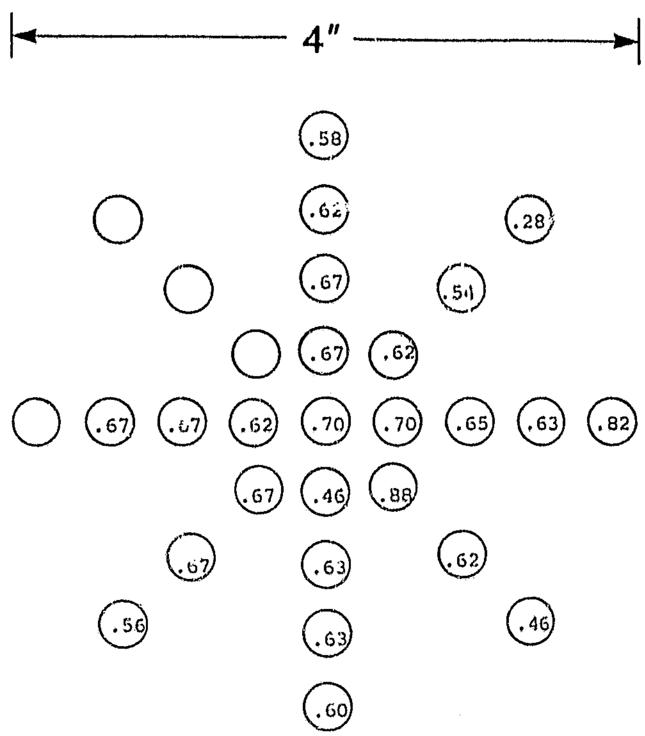


Agenda

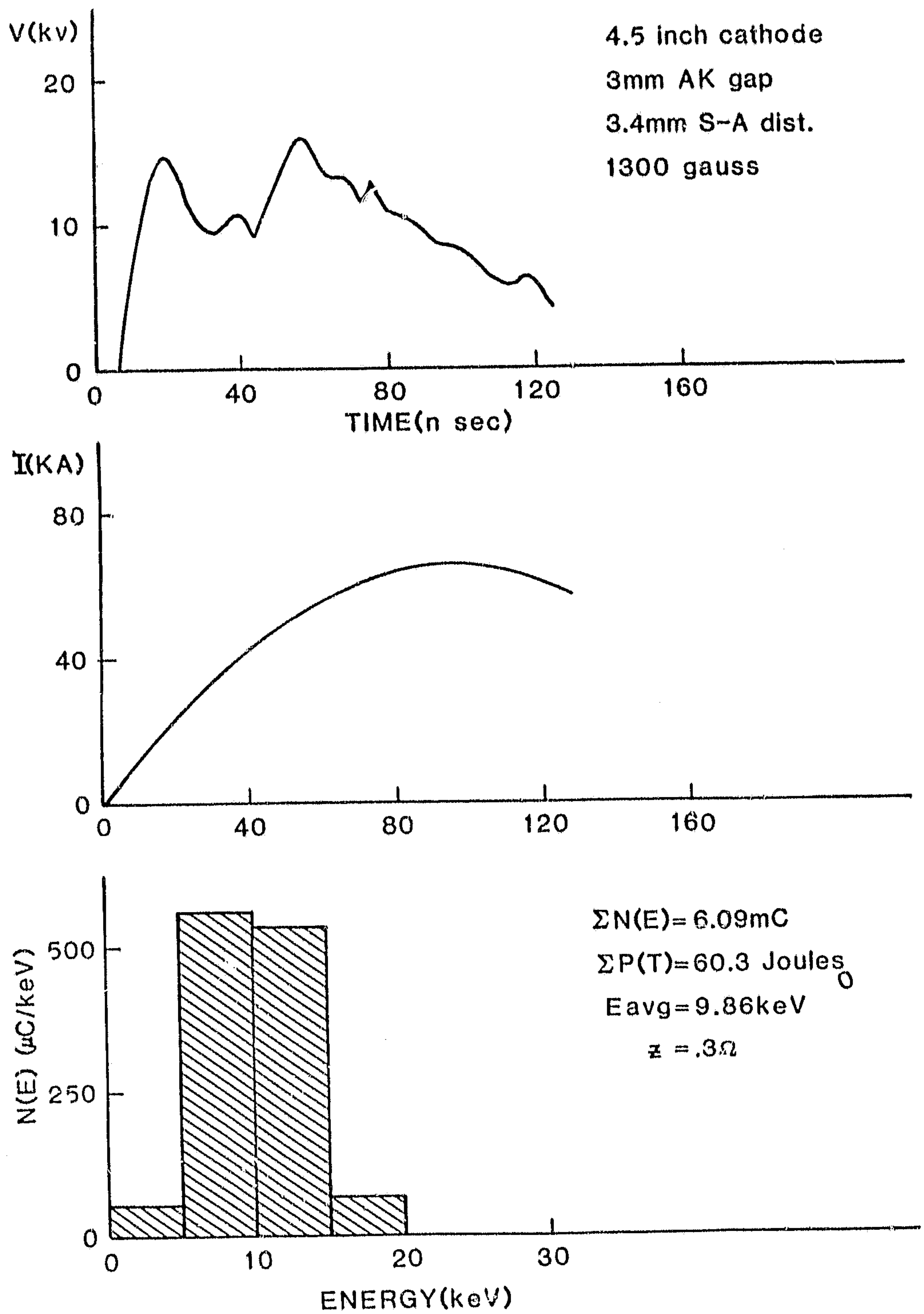
1. INITIAL TEST ANNEALS WITH ELECTRON BEAM PULSER
2. WAFER TRANSPORT SYSTEM
3. NON-MASS ANALYZED IMPLANTED CELL FABRICATION RESULTS
4. INITIAL DESIGN OF SOLAR CELL ION IMPLANTER

Calorimeter Readout:

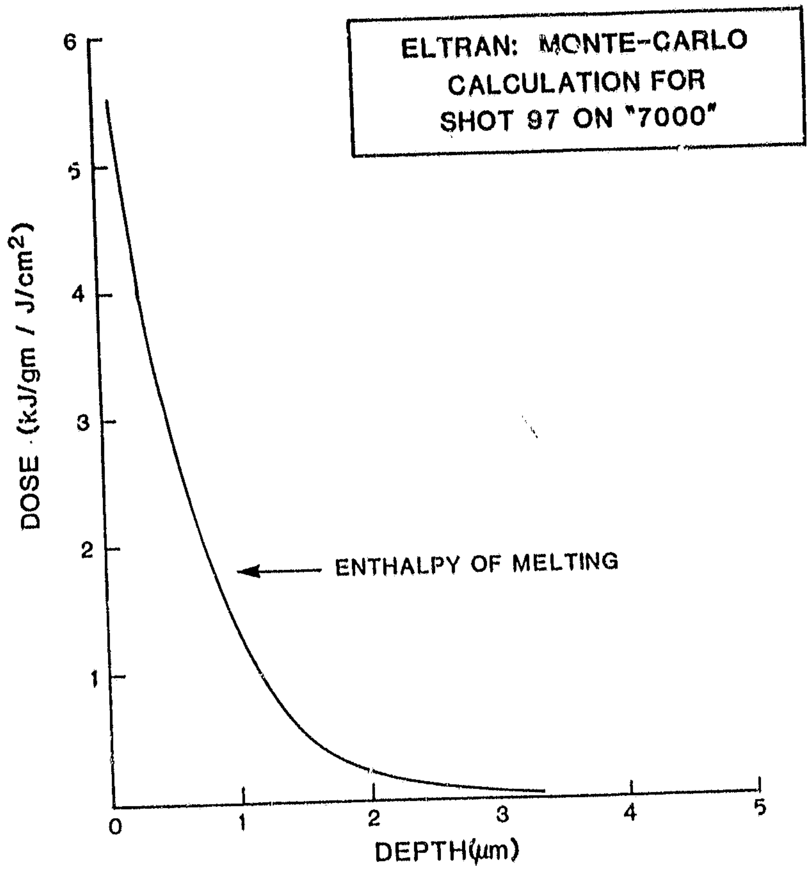
Average Reading on All Points, 0.64 ± 0.09 J/cm^2



SPI-Pulse 7000 Discharge Characteristics

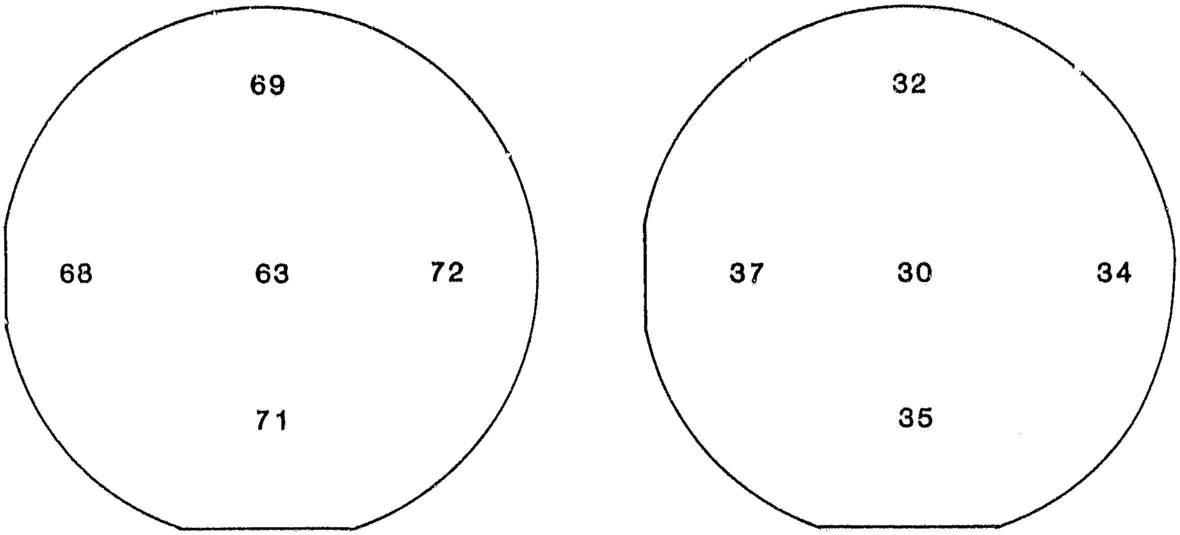


Absorbed Energy in Silicon
(Normalized to 1 J/cm^2 Fluence)



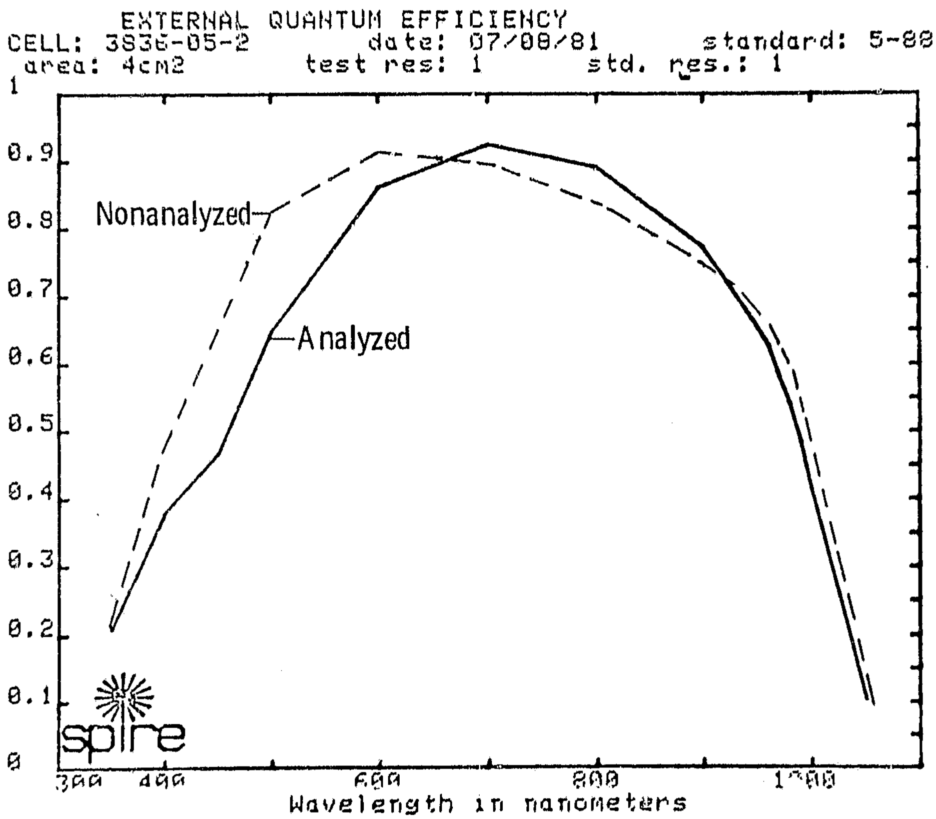
Sheet Resistance (ohms/square)

4-in. Si Wafers; 2×10^{15} $^{31}p^{+}/cm^{2}$ at 10 keV



FURNACE ANNEALED

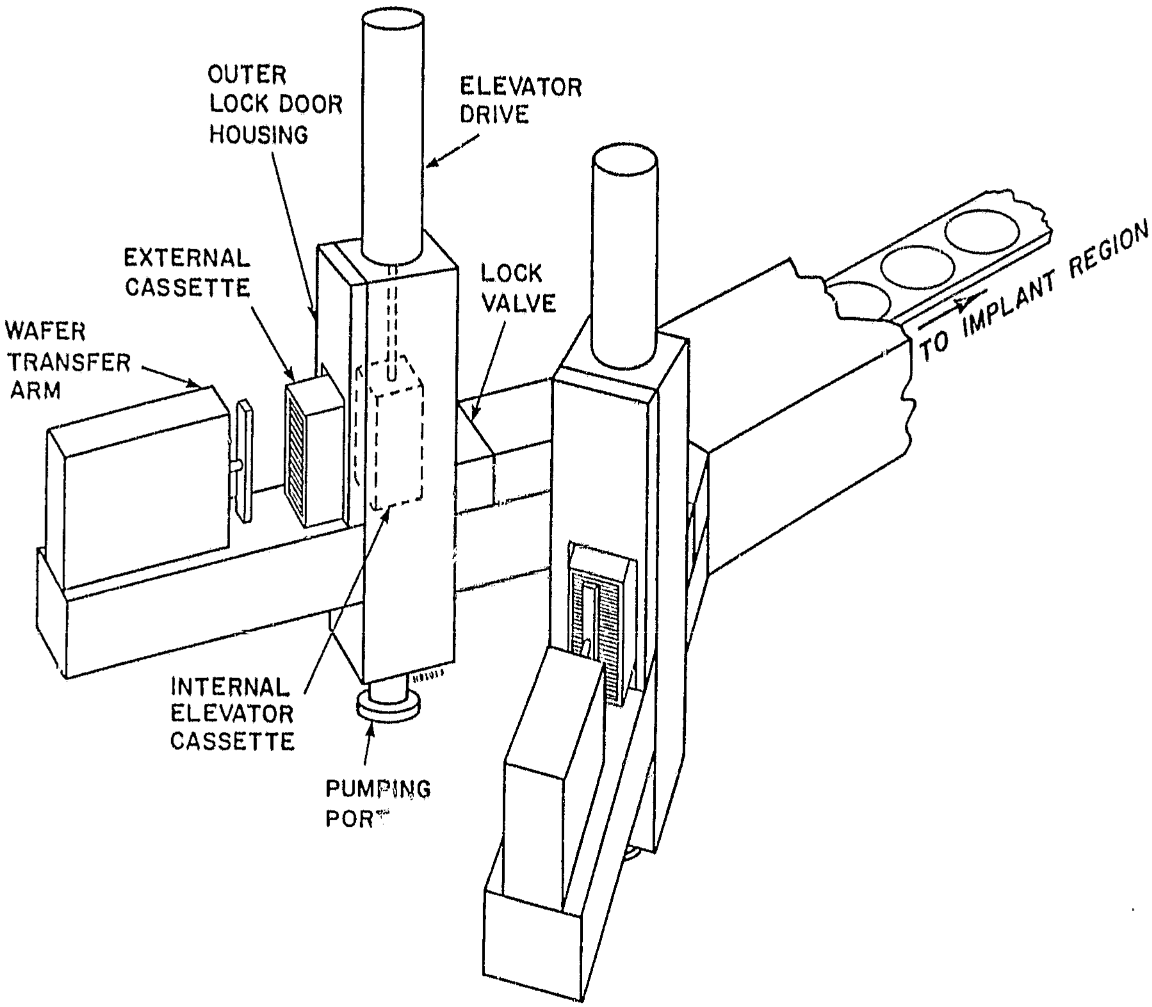
PULSE ANNEALED (7000)



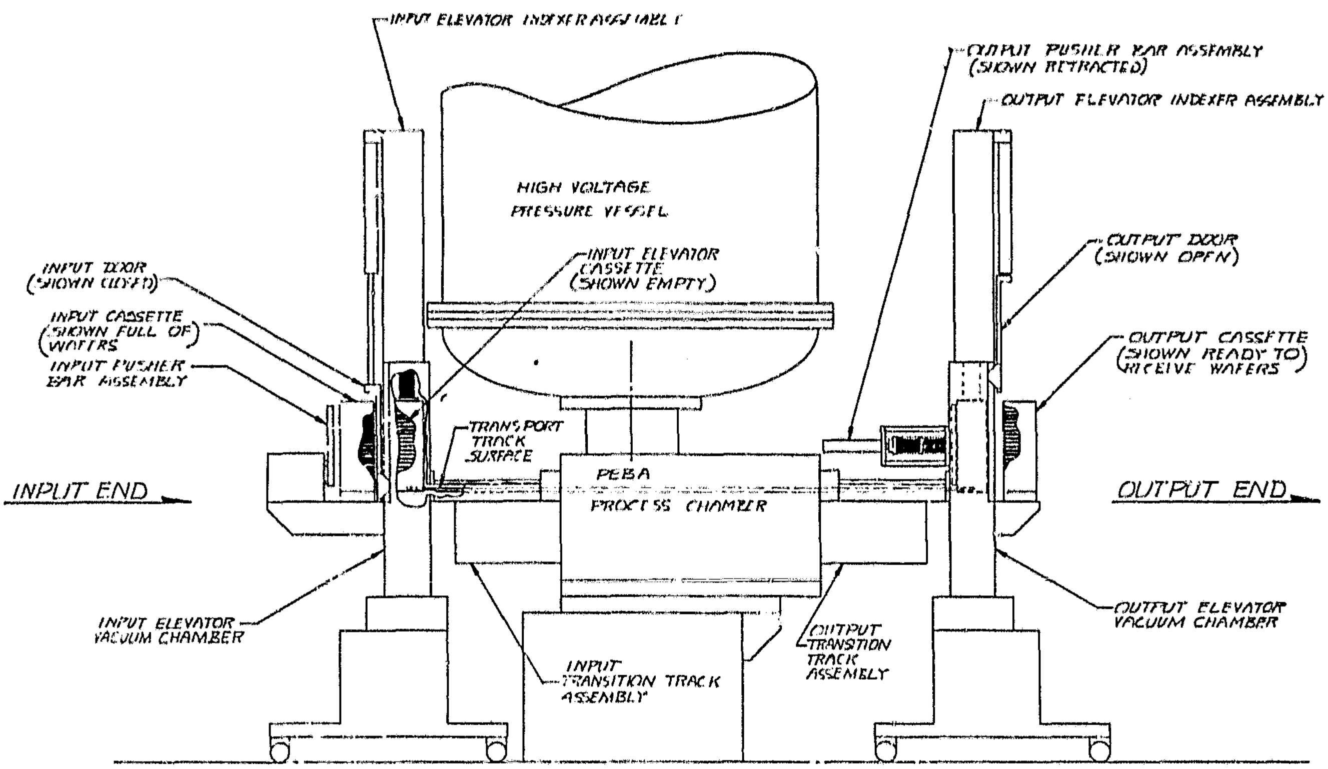
Lambda (nm)	QE
350	0.2104
400	0.3802
450	0.4681
500	0.6490
600	0.8618
700	0.9243
800	0.8909
900	0.7712
950	0.6515
960	0.6254
970	0.5803
980	0.5381
990	0.4819
1000	0.4144
1050	0.1044

Ln : 115 microns
R : 0.985

Y-Track Cassette Input Locks



Elevator-Chamber Integration



Summary of Pulse Annealer Progress

1. ANNEAL OF 4" DIA. WAFER - Done

2. VACUUM TRANSPORT AT 3 SECONDS/WAFER - Done

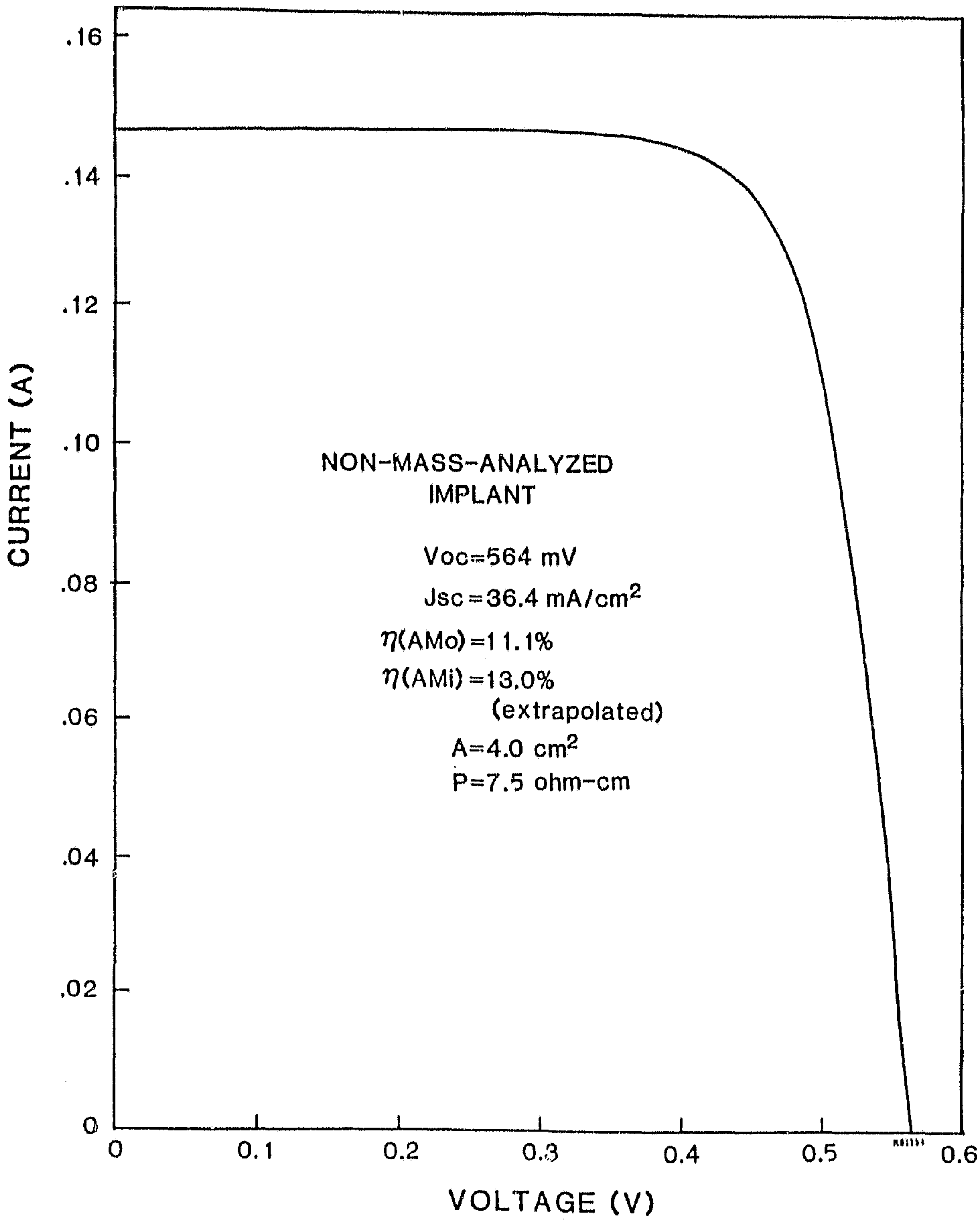
3. CHARGING PULSE IN 3 SECONDS - When 15 mA Power Supply Delivered - 7/21/81

4. SIMULTANEOUS DEMONSTRATION OF ABOVE ON 50 WAFERS - August

Non-Mass-Analyzed Ion-Implanted Cells: Preliminary Samples

- IMPLANT: Phosphorus, 3 x 10^{15} ions/cm^2, Implanted at JPL Cell Processing at Spire
- PURPOSE: Preliminary Comparison with Normal Cell Processing
- RESULTS: Cell Efficiency Lot Average Slightly Less than Normal Production. This Appears to be Caused by:
  1. Lifetime Lower than Expected
  2. Non-Optimum AR Coating Lowered J_{SC} (Minor Effect)
- CONCLUSIONS: More Cells will be Produced to Isolate Cause of Item 1.

Non-Mass-Analyzed Implant



Non-Mass-Analyzed Implant Cells

LOT NUMBER:	3836	RESISTIVITY:	10.0 ohm-cm
CONTRACT No:	10073	AR COATING:	TiO_2
ORIGINATOR:	S. Bunker	MATERIAL:	FZ
SURFACE:	Pol	THICKNESS:	15 Mils
COMMENT:	JPL Imp.	DATE:	07/01/81
CELL AREA:	4.0 cm^2	RATED VOLT:	0.400 V
ILLUMINATION:	AM0	TEMPERATURE:	25°C

Cell	Dose ($x10^{15}$)	Voc (V)	Jsc mA/cm^2	FF (%)	Eff. (%)	Rsheet Ohm/□
2	3	0.564	36.36	72.9	11.05	78
3	3	0.564	35.87	73.1	10.93	83
4	3	0.554	34.55	73.6	10.41	83
5	6	0.559	34.22	75.2	10.63	61
6	6	0.559	35.04	75.2	10.88	58
8	6	0.554	34.05	75.5	10.53	59
ave.		0.559	35.01	74.3	10.74	
sdv.		0.005	0.93	1.2	0.25	

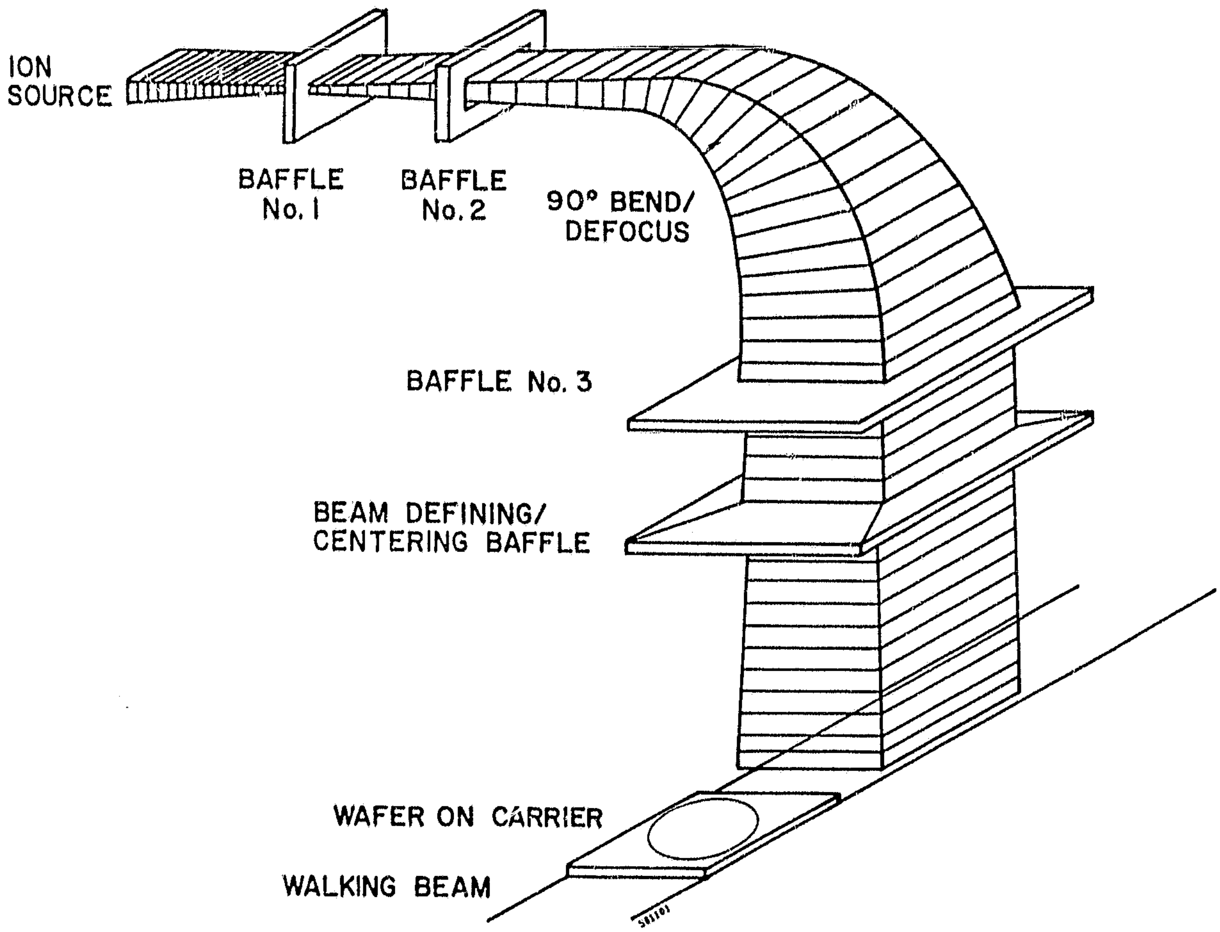
	Lot 3836 Non Analyzed Implant	Lot 2706 Standard Implant
Voc (mV)	564	587
Jsc (mA/cm^2)	36.4	38.8
Fill Factor (%)	72.9	77.0
η (AM0) (%)	11.1	12.8
η (AM1) - Extrapolated (%)	13.0	15.1
Lifetime* (μsec)	14.0	41.0
Diffusion Length+ (μm)	220	380
ρ (ohm-cm)	7.5	10
Cell Thickness (μm)	200	350

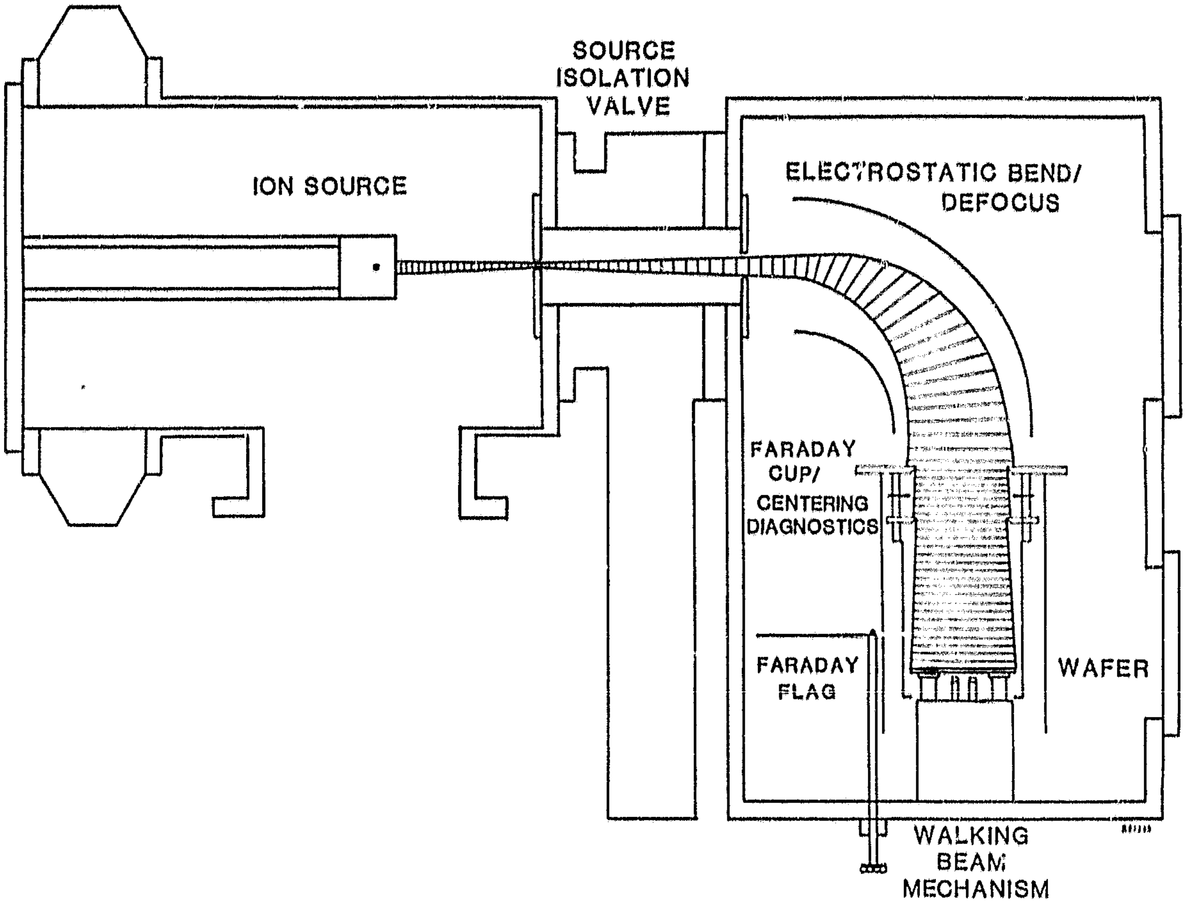
* Open-Circuit Voltage Decay Method
\+ Inferred from Lifetime

Solar-Cell High-Throughput Ion Implanter (Task 3)

- Implant Rate: 1800/hour, Walking Beam Transport
- Implant Ions/Dose: P_1^+, P_2^+, etc. @ 2.5×10^{15} ions/cm^2
- Ion Current: 2 Units @ 10-15 ma over ~ cm^2
- Ion Energy ~ 5-10 keV
- Diagnostics - Beam Current
  Beam Centering
  Transverse Uniformity
- Wafer Heating - 100^{0}C Rise for Two Sources

Ion Implanter Beam Profile





SILICON DENDRITIC WEB MATERIAL PROCESS DEVELOPMENT

WESTINGHOUSE RESEARCH & DEVELOPMENT CENTER

D. L. Meier

Contact Systems

1. **Baseline: Evaporated Ti Pd Ag, Plated Cu**
2. **First Experimental System: Evaporated Ti Ni Cu, Plated Cu**
3. **Second Experimental System: Evaporated Ni, Plated Cu, Heat-Treated to Form Ni_2Si**

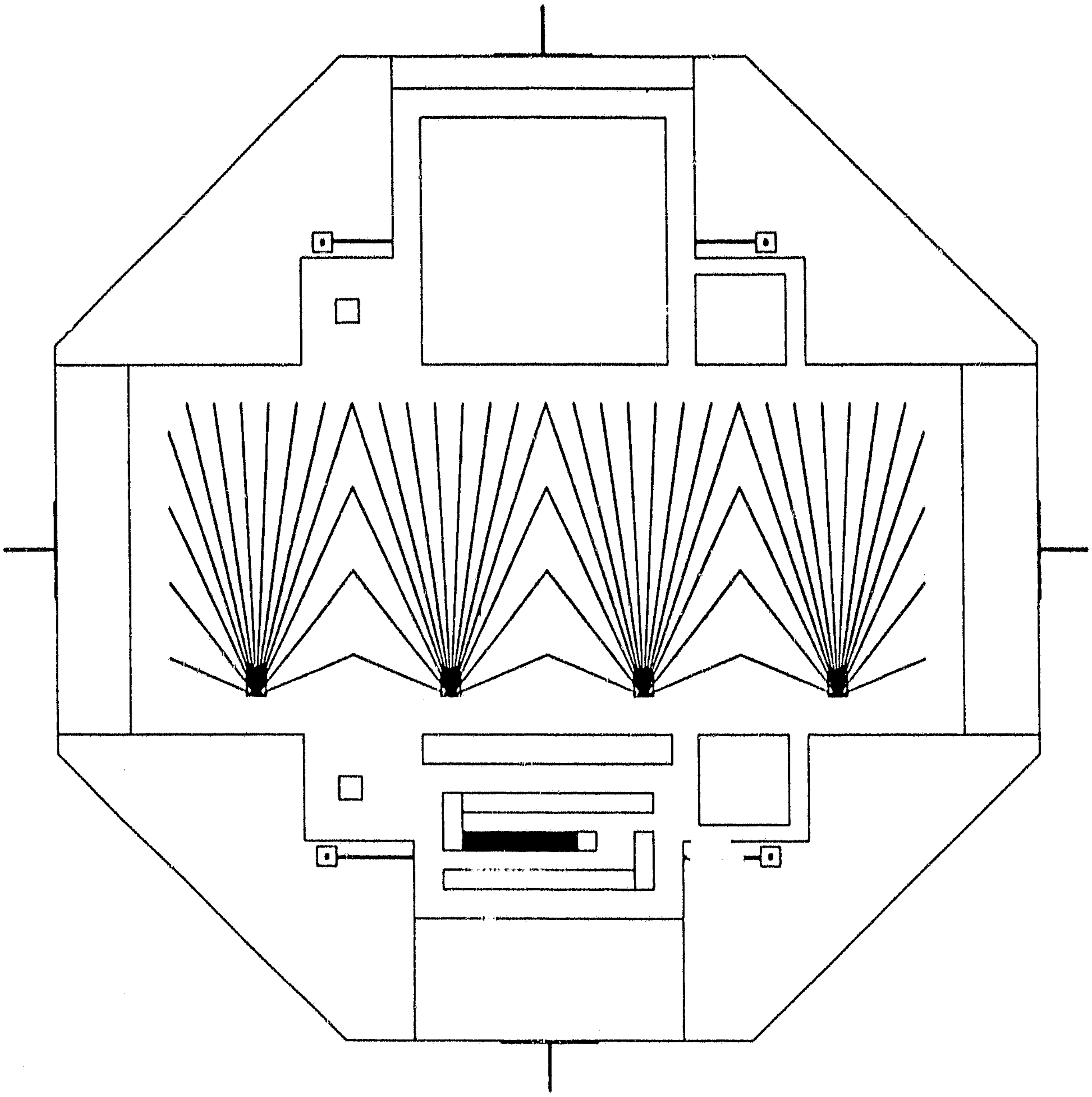
- **Also Investigate Plating a Ni Layer on the Plated Cu to Protect Cu from Oxidizing and to Provide a Better Galvanic Match to the Al Interconnects**

Contract Objectives

- Develop a Low-Cost Contact System for Solar Cells
- Fabricate Several Modules Using Dendritic Web Silicon

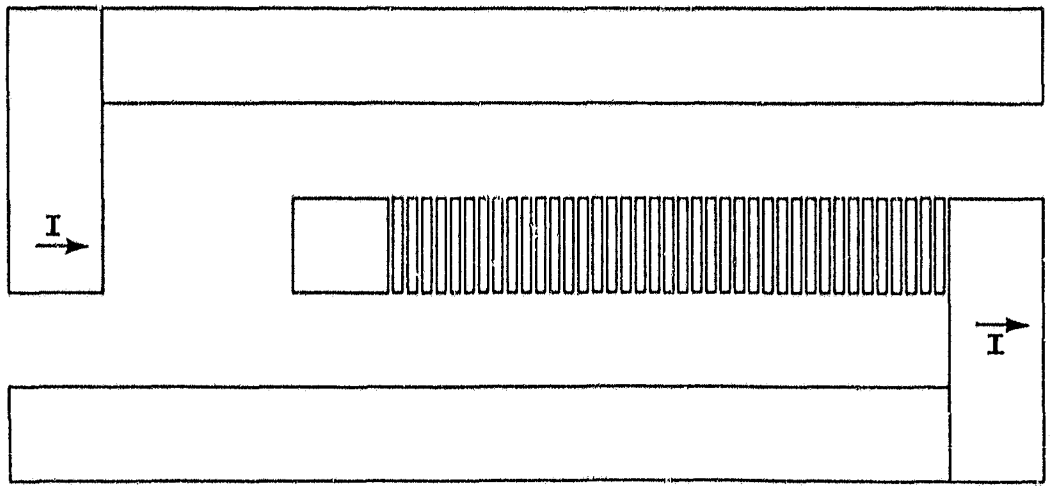
Solar Cell Contact Mask

- 1.6 x 4.0cm Solar Cell
- Contact Resistance Test Pattern
- Minority Carrier Lifetime Pattern



Contact Resistance Test Pattern

- **Current Repeatedly Passes From Diffused Silicon Substrate to Metal Bar and Back to Substrate**
- **Given the Pattern Geometry, R_c is Determined by Measuring Two Voltages and One Current (No Plots Are Required)**



Baseline Contact System: Typical Results

Material: FZ Silicon, 4Ωcm, <111>, 250μm Thick
Evaporated Metal: 500 Å Ti, 300 Å Pd, 300 Å Ag
Electroplated Metal: 5μm Cu
Heat Treatment: None

ID	J_{sc}	V_{oc}	Log (J_o)	FF	η	R_c
NB93	31.2 mA/cm^2	0.583 V	−10.4	0.789	15.7%	5.9×10^{-6} Ωcm^2
NB98	31.1	0.572	−9.1	0.770	15.0	3.6
NB4	29.3	0.584	−9.9	0.785	14.6	4.6

- Good Quality Cells With Low Contact Resistance Are Made With the Baseline System

First Experimental Contact System: Typical Results

Material: FZ Silicon, 4Ωcm, <111>, 250μm Thick
Evaporated Metal: 500 Å Ti, 400 Å Ni, 300 Å Cu
Electroplated Metal: 5μm Cu
Heat Treatment: None

ID	J_{sc}	V_{oc}	Log (J_o)	FF	η	R_c
NB86	31.2 mA/cm^2	0.584 V	−10.9	0.796	15.8%	5.9×10^{-6} Ωcm^2
NB64	30.3	0.577	−9.5	0.781	14.9	2.5
NB92	31.1	0.572	−8.2	0.762	14.8	11.7

- Replacing Pd and Ag With Ni Has no Effect on Cell Performance Prior to Thermal and Humidity Stressing

Typical Sintering Results

Material: FZ Silicon, 4Ωcm, <111>, 250μm Thick
Heat Treatment: 300°C for 15 Minutes in H_2

Baseline: Ti Pd Ag Cu (NB72)

	J_{sc}	V_{oc}	FF	η	R_s	R_c
Pre-Sinter	30.4 mA/cm^2	0.585 V	0.782	15.2%	0.113Ω	1.5×10^{-6} Ωcm^2
Post-Sinter	29.9	0.590	0.782	15.1	0.094	1.2

First Experimental: Ti Ni Cu (NB64)

	J_{sc}	V_{oc}	FF	η	R_s	R_c
Pre-Sinter	30.3 mA/cm^2	0.577 V	0.781	14.9%	0.133Ω	2.5×10^{-6} Ωcm^2
Post-Sinter	29.8	0.585	0.785	14.9	0.089	2.2

- No Degradation at 300°C for 15 Minutes for Either Contact System
- Series Resistance and Contact Resistance Decrease From Initial Low Values (Does Not Alter Cell Performance)

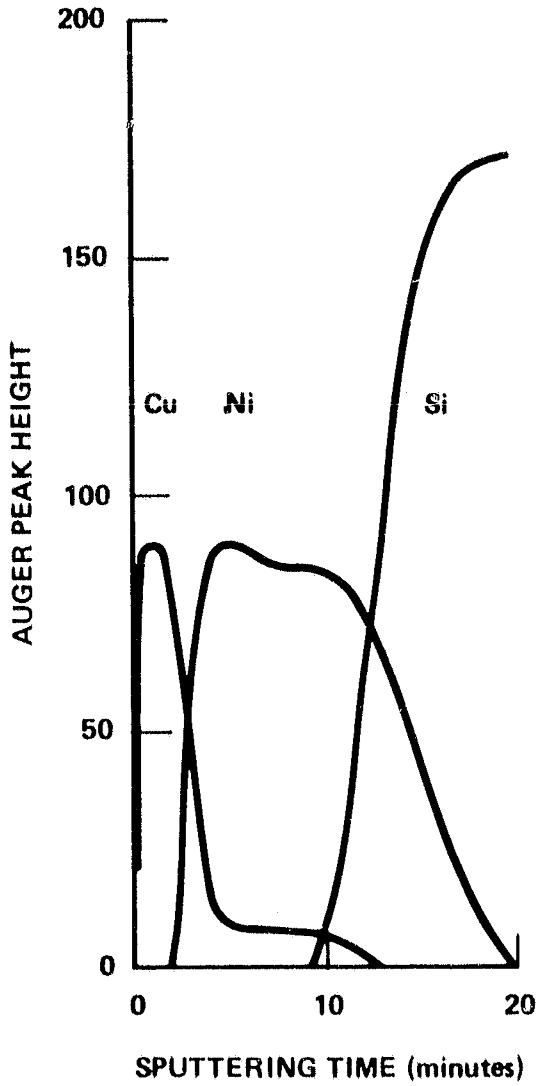
Ultrasonic Bonding of Aluminum Interconnect To Nickel-Coated Cell Pad

- Bonds are Excellent
- In All 24 Pull Tests the Aluminum Finger (1.5 Mil Thick) Yielded Before the Aluminum Could Separate From the Nickel
- The Layer of Nickel on the Electroplated Copper Does Not Appear to Degrade Cells

C-5-

Second Experimental Contact System

Material: FZ Silicon 4Ωcm <111>
Evaporated Metal: 600 Å Ni, 300 Å Cu
Heat Treatment: 300°C for 24 Minutes in H_2
Elemental Depth Profile by Auger Spectroscopy With Sputtering



- **Copper Appears to Have Penetrated ~ 400 Å Into the Ni**

Status of Ni-Cu System

- Poor Adherence of Metal System to Silicon for Initial Attempt with Evaporated Ni
- Additional Work in Progress Where Ni is Deposited by Sputtering After 100 Å of Si has Been Removed by Sputter Etching
- Indications are That Cu Can Penetrate Approximately 400 Å in 15 Minutes at 300°C. Thus, a Thin Layer of Ni May Not be an Adequate Diffusion Barrier for Cu.

ANALYSIS AND EVALUATION OF MEPSDU PROCESSES

UNIVERSITY OF PENNSYLVANIA

M. Wolf

OBJECTIVE: THE TECHNICAL ADVANTAGES AND DISADVANTAGES OF THE PROPOSED, DEVELOPED, OR ALTERNATE MEPSDU PROCESSES WILL BE EVALUATED. ATTENTION WILL BE FOCUSED ON THE IMPACTS OF THE PROCESS INTERFACES AND SEQUENCES. THE AVAILABLE DATA WILL BE EXAMINED WITH RESPECT TO THE PROJECTED PROCESS COSTS, WITH PARTICULAR ATTENTION TO BE PAID TO CRITICAL INDIRECT MATERIALS AND EXPENDABLE TOOLING.

STATUS: REPORTS RECEIVED, ORGANIZED, AND READ (WITH NOTATIONS IN MARGINS).

PROCESS DEVELOPMENT AREA

JPL IN-HOUSE ROBOTICS

JET PROPULSION LABORATORY

T.L. Brooks and R. Cunningham

Task Objective

APPLICATION OF ADVANCED ROBOTIC AND MACHINE PERCEPTION TECHNIQUES TO SOLAR CELL MODULE PRODUCTION.

Milestones to Date and Planned

- AUTOMATION EVALUATION STUDY TO IDENTIFY POTENTIAL APPLICATIONS OF MACHINE INTELLIGENCE
  1) STRAWMAN BASED ON 1978 JPL PROCESS SEQUENCE (OCTOBER 1980)
  2) AUTOMATION EVALUATION STUDY FINAL REPORT (IN PROGRESS)
- LAB DEMONSTRATION OF SELECTED DEVELOPMENT TASK(S)
  1) SOLAR CELL LAYUP USING COMPUTER VISION (FEBRUARY 1981)
  2) ATTACHMENT OF POWER-OUT CONNECTOR TO SOLAR CELL MODULE (JULY 1981)
  3) SOLDERING OF POWER-OUT TAB TO SOLAR CELL MODULE (SEPTEMBER 1981)
  4) INTEGRATION OF ITEMS 3 & 4 TO DEMONSTRATE TOTALLY AUTOMATED CONNECTOR ASSEMBLY SYSTEM (OCTOBER 1981)

Demonstration Task Scenario No. 2

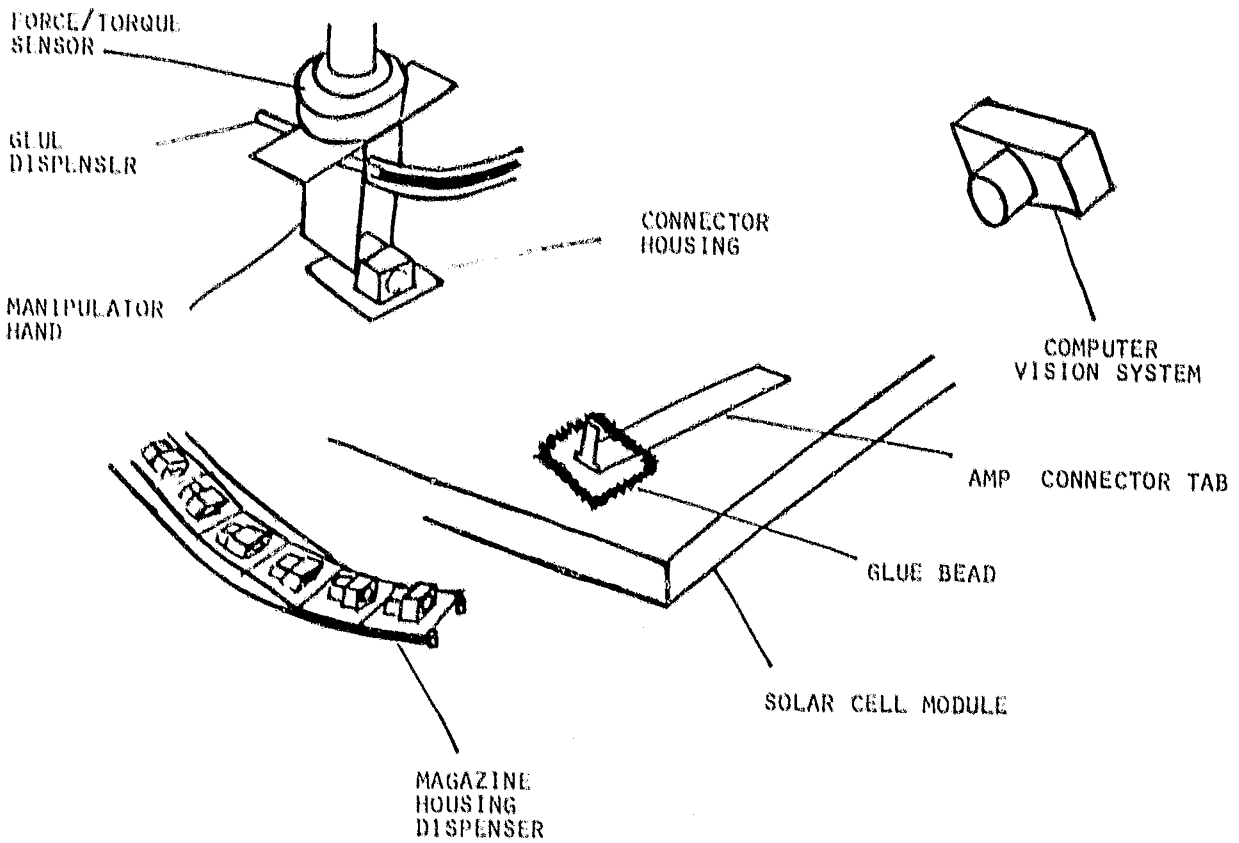
CONCURRENT PROCESSES
- PICK UP CONNECTOR HOUSING FROM MAGAZINE
- DETERMINE CONNECTOR TAB LOCATION WITH COMPUTER VISION

- MOVE TO TAB LOCATION AND LAY DOWN GLUE BEAD

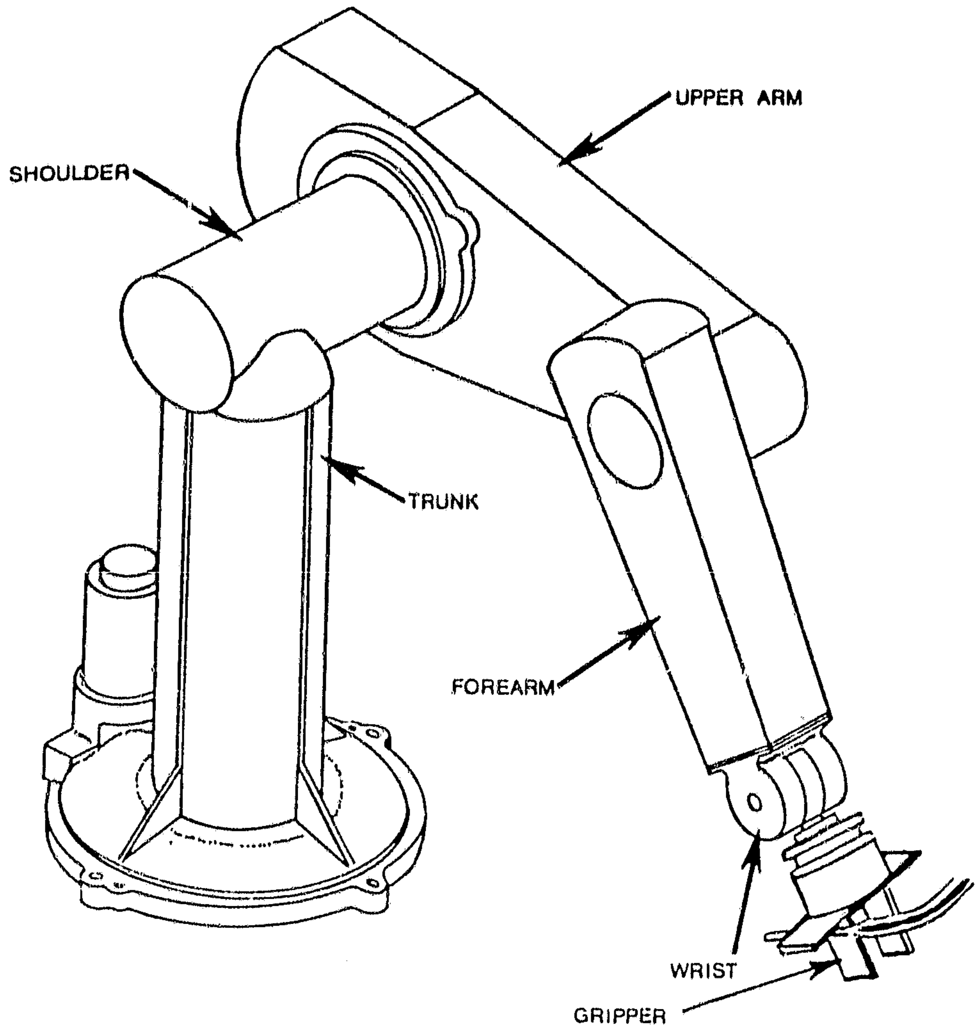
CONCURRENT PROCESSES
- VISUALLY INSPECT GLUE BEAD FOR WIDTH, BREAKS AND POSITIONING
- ORIENT HAND ABOVE TAB READY FOR INSERTION OF TAB INTO HOUSING

- MOVE HAND DOWN UNTIL HOUSING CONTACTS TAB
- CONTACT SENSED THROUGH CONTINUOUS MONITORING OF FORCE FEEDBACK
- SLIDE HOUSING ACROSS TAB UNTIL TAB "POPS" INTO SLOT
- "POP" SENSED BY SUDDEN ABSENCE OF CONTACT FORCE
- SLIDE HOUSING DOWN ON TAB AND SEAT IN GLUE
- RELEASE HOUSING AND START NEXT CYCLE

Components of Robotic System for Automated Attachment of Power-Out Connector



PUMA Robot for Advanced Automated Solar-Cell Module Production



Vision System Features

- ADAPTS TO CHANGES IN THE ABSOLUTE LOCATION AND ORIENTATION OF AMP CONNECTOR TAB
- INSPECTS GLUE BEAD FOR WIDTH, BREAKS, AND POSITIONING
- EASILY PROGRAMMED TO HANDLE DIFFERENT CONNECTOR CONFIGURATIONS

Robot System Features

- ADAPTS TO VARIABLE TAB LOCATION AND ORIENTATIONS
- ADAPTS TO TAB HEIGHT INCONSISTENCIES
- USES FORCE FEEDBACK INFORMATION TO PREVENT DAMAGE TO CONNECTOR HOUSING AND TAB
- CONTROLS GLUE BEAD LAYUP TO GIVE CONSISTENT SEALS

System Goals

- ATTACH, SEAL AND INSPECT CONNECTORS ON ONE MODULE PER MINUTE (ASSUMING 25 MW PLANT)
- MAINTAIN SYSTEM COSTS LESS THAN $150K

Key Points

- AUTOMATION OF LABOR INTENSIVE TASK
- SYSTEM COST WITH OFF-THE-SHELF TECHNOLOGY ~$100K
- PRESENT SYSTEM CAPABLE OF BETTER THAN TWO CONNECTORS PER MINUTE
- BOTTOM LINE - ONE ROBOT SYSTEM CAN HANDLE OUTPUT OF 25 MW PLANT

Other Lab Activities Since 17th PIM

PUMA

- INSTALLED AND RUNNING UNDER VAL
- INTERIM INTERFACE TO SPC-16 FOR SENSORY FEEDBACK TO PUMA COMPLETED
- MODIFICATION OF JARS (JPL AUTONOMOUS ROBOT SYSTEM) TO CONTROL PUMA ONGOING
- HAND AND FORCE/TORQUE SENSOR INSTALLED ON PUMA

COMPUTER VISION SYSTEM

- WORK ON IMFEX (REAL-TIME IMAGE PROCESSING DEVICE) ONGOING

NON-MASS-ANALYZED ION IMPLANTS

JET PROPULSION LABORATORY

Dennis Fitzgerald

Current Objectives

- FIND EFFECT OF (DIFFUSED) BSF ON CELL WITH N-M-A JUNCTION
- IMPLANT N-M-A JUNCTIONS AND BSF WITH GASEOUS SOURCES
- N-M-A IMPLANT PHOSPHOROUS FOR WESTINGHOUSE AND SPIRE FOR THEIR EVALUATION
- FABRICATE COMPLETE CELLS USING N-M-A IMPLANTATION AND RECOMMENDED ANNEALING STEPS

NMA Junctions With Diffused BSF

DOSE (ATOMS/CM^2)	Voc(MAX) (MV)	Voc(AUG) (MV)	Isc (MA/CM^2)	η(AMO) %	F.F. %	BSF?
3×10^{15}	538	525	34.5	9.15	68	NO
3×10^{15}	560	547	36.2	9.25	63	YES
6×10^{15}	538	535	35.5	9.93	71	NO
6×10^{15}	574	570	37.6	11.13	70	YES
CONTROLS*	546	541	34.6	10.0	72	NO
CONTROLS*	578	577	36.6	11.27	72	YES

* DIFFUSED JUNCTION (APPLIED SOLAR ENERGY CORPORATION)

NMA Implant With Gaseous Sources

- HOLLOW CATHODE FREEMAN SOURCE DID NOT PERFORM WELL ON PF_5 AND BF_3
- ION SOURCE CONVERTED TO CONVENTIONAL REFRACTORY CATHODE CONFIGURATION FOR EVALUATION OF GASES
- PF_5 IMPLANTS (FX-MATERIAL) FOR WESTINGHOUSE DID NOT WORK
- PF_5 IMPLANTS AT ASEC IN PROCESSING
- FILAMENT ION SOURCE RAN WELL ON BOTH GASES

Westinghouse-Spire NMA Evaluation

NAME	DOSE (ATOMS/CM^2)	COMMENTS	F.F. (%)	η (AMO) (%)	Isc (MA)	Voc (MV)
WESTINGHOUSE*	2×10^{15}	MA(GcA)	77	9.59	84.8	563
WESTINGHOUSE*	3×10^{15}	NMA(JPL	72	9.29	89.6	544
WESTINGHOUSE*	N/A	DIFFUSED	77	9.86	86.8	560
SPIRE**	3×10^{15}	NMA(JPL)	75	10.67		
	6×10^{15}	NMA(JPL)	75	10.79		

*F-Z, 4ΩCM, BSF, NO AR COATING

**C-Z, 10ΩCM, BSF, WITH AR COATING

Fabrication of NMA Cells at JPL

BACK DOSE (ATOMS/CM^2)	Voc (MV)	Isc (MA)	F.F. (%)	η (AM1)* (%)
0	496	81.3	54	5.42
2.5×10^{15}	518	79.2	62	6.33
5.0×10^{15}	522	80.2	65	6.73
1.0×10^{16}	526	79.6	65	6.82

BACK: N-M-A BF_3 12.5KV, 10^0, VARIABLE DOSE
FRONT: N-M-A P 12.5KV, 10^0, 5×10^{16} ATOMS/CM^2.

* NO AR COATING

MATERIAL & PROCESS RESEARCH FOR MODULE ASSEMBLY BY VACUUM LAMINATION

JET PROPULSION LABORATORY

Dale R. Burger

Equipment Development

- TSONGAS LAMINATOR
- EVA MODIFICATION
- FUTURE CHANGES

Process Verification

- SPECTROLAB PROCESS
- ADHESION PROBLEMS
  - EVA TO BACK SHEET
  - SOLDER FLUX
- GEL TEST

Material Research

- EVA-GLASS
- EVA-PVF
- EVA-POLYESTER
- EVA-ACRYLIC
- EMA SYSTEM

Other Research Efforts

- LAMINATOR OPERATION
- MECHANICAL TESTS
- SOLDER FLUX REMOVAL
- MATERIAL HANDLING

Conclusions

- CHOICE OF MATERIALS
- LOW-COST LAMINATOR
- CHEMICAL BONDING
- MATERIAL HANDLING

TECHNOLOGY TRANSFER: LSA PROJECT TO INDUSTRY

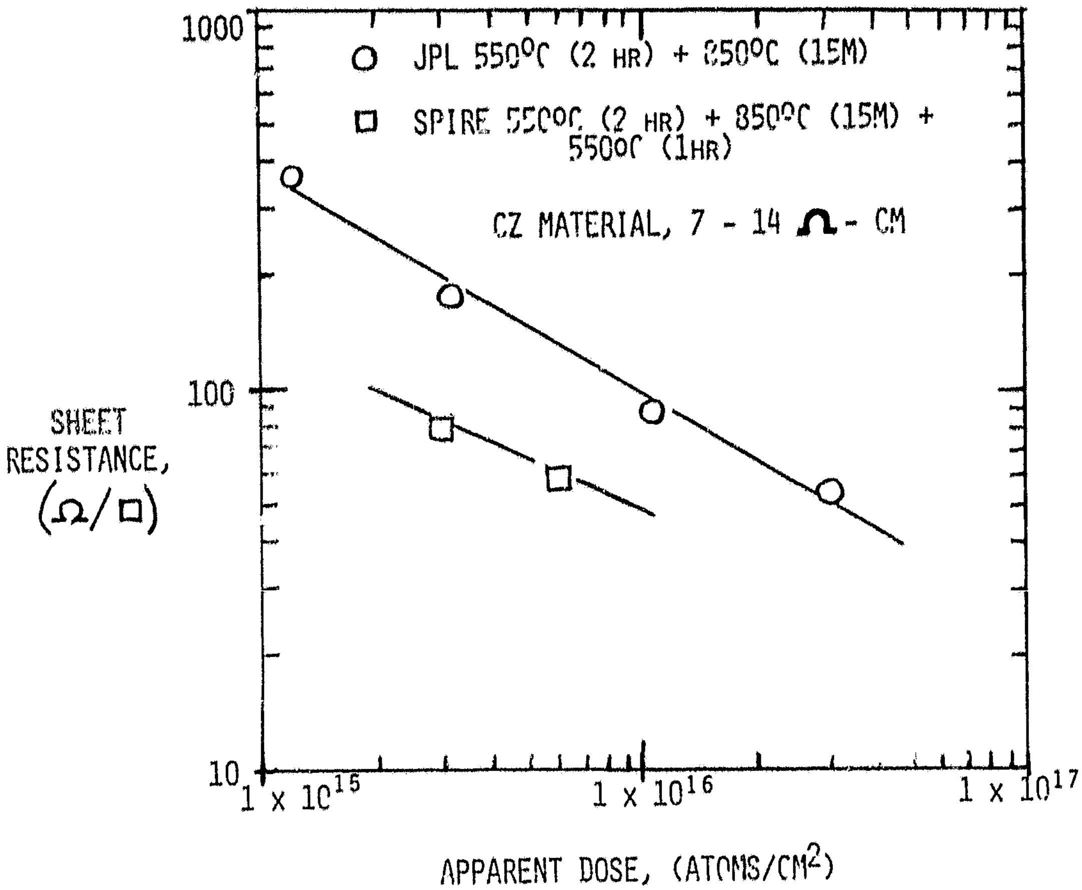
JET PROPULSION LABORATORY

B.D. Gallagher

Objective

- PROMOTE ADVANCEMENT OF PV INDUSTRY
- OBTAIN INFORMATION ON ADEQUACY OF SPECS

Sheet Resistance vs Dose



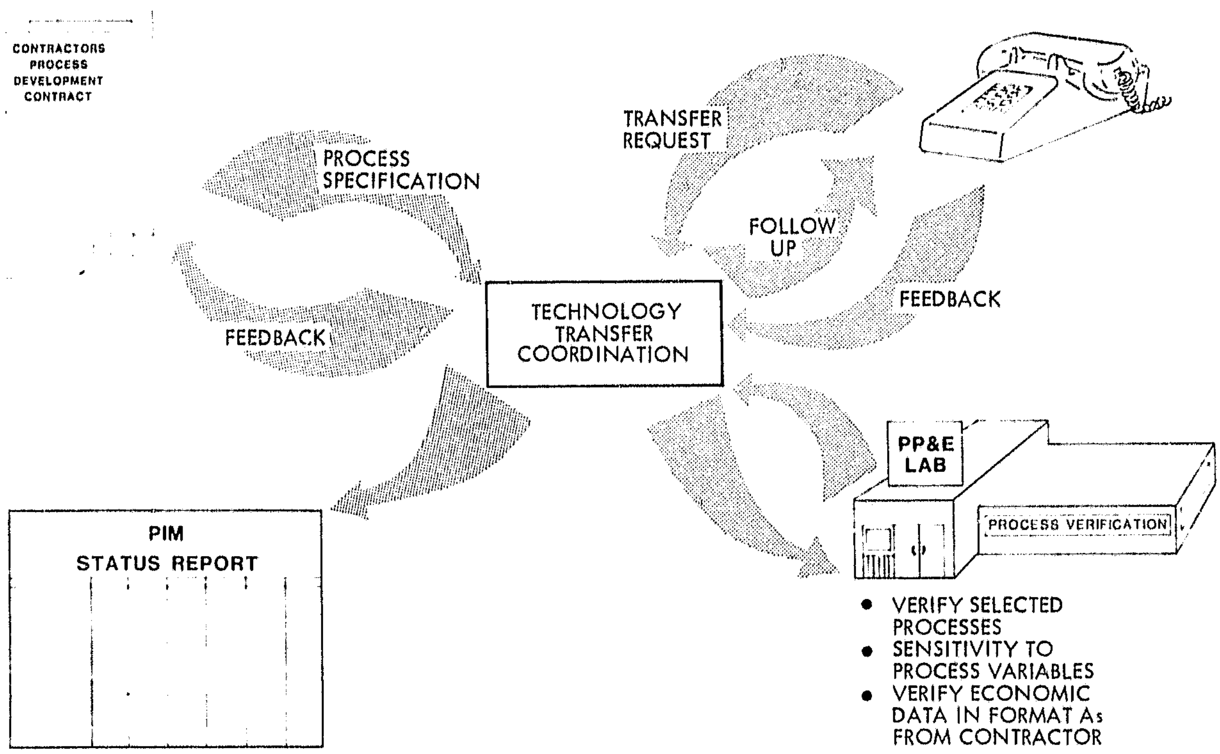
Conclusions

- N-M-A JUNCTIONS WITH DIFFUSED BSF COMPARED WELL WITH DIFFUSED CONTROLS (ASEC)
- WESTINGHOUSE/SPIRE EVALUATION SHOWS REDUCED MINORITY CARRIER LIFETIME WITH N-M-A P
- FIRST N-M-A CELLS MADE AT JPL HAD LOW F.F. AND Voc BUT SHOWED IMPROVEMENT WITH BSF
- TESTS SHOW POSSIBLE BAD ACTORS IN N-M-A ION BEAM AND/OR THERMAL ANNEAL PROBLEMS

Caveats

- INFORMATION IS TRANSFERRED BY INDUSTRY REQUEST ONLY
- EVALUATION IS NOT A JPL-FUNDED EFFORT
- THESE SPECIFICATIONS WERE PREPARED AS AN ACCOUNT OF WORK SPONSORED BY THE UNITED STATES GOVERNMENT. NEITHER THE UNITED STATES NOR THE UNITED STATES DEPARTMENT OF ENERGY, NOR ANY OF THEIR EMPLOYEES, NOR ANY OF THEIR CONTRACTORS, SUBCONTRACTORS, OR THEIR EMPLOYEES, MAKES ANY WARRANTY, EXPRESS OR IMPLIED OR ASSUMES ANY LEGAL LIABILITY OR RESPONSIBILITY FOR THE ACCURACY, COMPLETENESS OR USEFULNESS OF ANY INFORMATION, APPARATUS, PRODUCT OR PROCESS DISCLOSED, OR REPRESENTS THAT ITS USE WOULD NOT INFRINGE PRIVATELY-OWNED RIGHTS.

Transfer Procedure



Process Categories

- SURFACE PREPARATION
- METALLIZATION
- JUNCTION FORMATION
- MODULE ASSEMBLY

Metallization

PROCESS	CONTRACTOR	STATUS	SURVEYED BY	COMMENTS
ALUMINUM BACK CONTACTS	ARCO SOLAR	EVALUATED	WESTINGHOUSE	CONFIRMED
		UNDER EVAL.	GENERAL ELECTRIC	
			SOLAR POWER	
			UNIV. OF PENN.	ECONOMIC ONLY
THICK FILM	LOCKHEED	UNDER EVAL.	GENERAL ELECTRIC	
			UNIV. OF PENN.	ECONOMIC ONLY
FRONT CONTACT FORMATION	MB ASSOC.	UNDER EVAL.	SOLAR POWER	
ELECTROLESS Pd/Ni	MOTOROLA	EVALUATED	APPLIED SOLAR ENERGY	CONFIRMED
			PHOTOWATT	CONFIRMED
			SOLAMAT	CONFIRMED
			SOLAREX	CONFIRMED
			SOLAR POWER	CONFIRMED
			WESTINGHOUSE	CONFIRMED (MOD)
		UNDER EVAL.	ARCO SOLAR	
			NASA LEWIS	
			UNIV. OF DELAWARE	ECONOMIC ONLY
			UNIV. OF PENN.	ECONOMIC ONLY

Status

	AVAILABLE	UNDER EVALUATION	CONFIRMED
SURFACE PREP.	21	15	5
JUNCTION FORMATION	25	16	6
METALLIZATION	18	11	3
MODULE ASSEMBLY	28	13	0
TOTALS	92	55	14

ENGINEERING AREA
OPERATIONS AREA

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JOINT TECHNOLOGY SESSION R. G. Ross and L. D. Runkle, Chairmen

Presentations from the Operations and Engineering Areas were offered in two joint technology sessions. Summaries of the presentations and reproductions of the visual materials that were presented are given below.

S. E. Forman of MIT Lincoln Laboratory reported on the module-procurement experience and module field performance at the Southwest and Northeast Residential Experiment Stations and at the innovative PV installations in Arizona, Florida and Hawaii. Histograms showing peak-power distributions of modules as received, discussions and illustrations of the quality of modules as received, performance curves and photographs of the installations were features of the presentation.

L. D. Runkle, LSA Operations Area manager, spoke on the performance and reliability of modules and the relations between field testing experience and the development of qualification testing. He emphasized that qualification testing is a step in the design process, and that implications drawn from such testing do not include any guarantees or certifications of module performance.

P. Jaffe reviewed the JPL field-testing experience and described test restructuring aimed toward early detection of module-failure modes, especially those that are triggered by arraying the modules. Endurance testing will continue, but with less emphasis.

R. W. Weaver of JPL described some details of a portable data logging device for field use and discussed the configuration of a test field for optimal data recovery.

A. H. Wilson of JPL discussed inexpensive techniques for cleaning flat-plate photovoltaic arrays that have been exposed to atmospheric soiling. Artificially and naturally soiled materials have been cleaned using a variety of detergent solutions. A commercially available detergent has proven to be effective in cleaning soiled glass samples exposed to an oil-refinery atmosphere. Unlike most glass samples tested, the oily samples were not effectively cleaned with multiple water washes.

The Clemson University accelerated-stress testing reliability study on silicon solar cells was presented by J. Lathrop. Twelve different cell types have been tested for reliability-attribute data and a wide range of differences in cells metallized by different techniques (i.e., vacuum deposition, plating, screen printing or soldering) were noted. Significant findings were presented from the wide range of stress tests performed on cells made with plated (copper) metallization and from a comparison test of electrical degradation in unencapsulated cells vs encapsulated cells. After the presentation, three cell manufacturers indicated their desire to participate with new cell types in the next round of testing at Clemson.

A. R. Hoffman of JPL compared U.S. and foreign environmental-testing criteria, including descriptions, test levels and field data. Foreign

requirements, initially based on JPL specifications, are further influenced by field experience and International Electrotechnical Commission requirements. Similarities exist for most mechanical and electrical stress tests but research must address differences in humidity, freeze, temperature-humidity soak and UV tests.

D. M. Moore's presentation at the 16th PIM, "Cell Interconnect Fatigue Life Prediction," showed a strong correlation between the predicted fatigue life of the cell interconnects on a Block II glass-fiber substrate module and identical field-application modules. Interconnect strain was predicted using a finite-element model that agreed with Manson's empirical fatigue curve for copper and correcting for the exposure (cycles) at the Schuchuli, Arizona, application site. At the 18th PIM, Moore presented a nomograph of the finite element model. Its usefulness was demonstrated; it permits the module designer to predict strain and fatigue life of various interconnect designs easily.

S. D. Glazer of JPL discussed a series of hot-spot tests performed under back-bias conditions on several modules by C. C. Gonzalez and E. S. Jetter. He also included the results of an analytical thermal model that predicts peak cell temperatures with back bias. Comparison of model predictions with data taken during the hot-spot tests showed good agreement for most module designs.

N. Shepard of General Electric Co. provided details of the integrated residential PV module-array concept selected for optimization. The design emphasis is on lower total cost through reduced material content and an integral mounting scheme with features that accommodate direct or standoff mounting. The modules mount directly on interlocking, roll-formed support sections that are attached to 2 x 4-in. purlins fastened directly to the roof rafters. Waterproofing is accomplished by horizontal module overlap and vertical closure strips. Module production and installation cost data were presented.

G. Royal of the American Institute of Architecture Research Corp. (AIA/RC) summarized work being done on the integrated residential PV module array involving eight architectural design teams that provided 15 concepts for initial consideration. The Burt Hill Kosar Rittelmann Associates concept was selected for detailed optimization. Preliminary estimates of cost data for module production, hardware fabrication, shipping and handling, installation, and operation were presented.

A. Levins of Underwriters Laboratories, Inc., reported on the progress of module and array safety requirements work in the area of the Interim Standard for Safety: Flat-Plate PV Modules and Panels (JPL Internal Document No. 5101-164), emphasizing the need for compatability with, and recognition of, the requirements being proposed by a separate National Electrical Code Ad Hoc Subcommittee on Photovoltaics. In addition, generic aspects of safety systems relating to electrical shock and ground faults with their associated potential for fire hazards were discussed. Details of an arc detector, still in the concept development stage, were presented.

The effects of dynamic wind loads on flat-plate photovoltaic arrays were discussed by R. Miller of Boeing. The analysis combined structural dynamics with wind characteristics. The resulting load magnification factors were then applied to known pressure loads to determine design loads. Magnification factors as high as 1.8 were found for the shielded arrays in mid-field. The upper

bound on the design load for 90 mph winds and a single array in an open area were shown to be 22 to 25 lb/ft^2.

An open session on reliability of modules addressed questions raised in earlier sessions. R. Willis of Solenergy Corp. was especially concerned with findings presented in a recent U.S. Coast Guard report that indicated that in a severely moist environment PVB has some limitations. A. R. Hoffman reviewed this report for the participants, and the matter was taken under advisement. User interest in qualification and warranties was expressed.

MODULE PROCUREMENT EXPERIENCE AND MODULE FIELD PERFORMANCE AT MIT LINCOLN LABORATORY RESIDENTIAL TEST FACILITIES

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

S.E. Forman

MIT-LL Residential Photovoltaic Test Facilities

1. NORTHEAST RESIDENTIAL TEST STATION (NERES)
   - o 5 PROTOTYPES IN CONCORD, MASS.
   - o 1 ISEE IN CARLISLE, MASS.

2. SOUTHWEST RESIDENTIAL TEST STATION (SWRES)
   - o 8 PROTOTYPES IN LAS CRUCES, N.M.

3. INNOVATIVE PV APPLICATIONS FOR RESIDENCES (IPAR)
   - o ARIZONA, FLORIDA, HAWAII (3)

NE RES, SW RES, ISEE and IPAR Procurement Experience

- DIRECT PROCUREMENT OF 120 BLOCK IV SOLAREX MODULES FOR LL PROTOTYPE AT NERES
- DIRECT PROCUREMENT OF 132 BLOCK IV SOLAREX MODULES FOR CARLISLE ISEE
- INDIRECT PROCUREMENT OF A MINIMUM OF 2 PRE-PRODUCTION PROTOTYPE MODULES FOR EACH OF 12 RESIDENTIAL PROTOTYPES
- IN-SITU VISUAL INSPECTION OF MODULES AT IPAR SITES

Northeast Residential Test Station at Concord MA
Site Operator: MIT-LL

PRIME CONTRACTOR	# OF MODULES	ARRAY CIRCUITRY	RATED POWER 25°C
TRISOLAR	36 ASEC INTEGRAL	1 BRANCH CIRCUIT 2 IN PARALLEL x 18 IN SERIES	4.8 KW
GENERAL ELECTRIC	375 GE SHINGLE	1 BRANCH CIRCUIT 15 IN PARALLEL x 25 IN SERIES	6.8 KW
SOLAREX	80 SX STANDOFF	5 BRANCH CIRCUITS 16 IN SERIES x 5 IN PARALLEL	(EST) 5.3 KW
WESTINGHOUSE	160 ARCO INTEGRAL	1 BRANCH CIRCUIT 12 IN PARALLEL x 13 IN SERIES	5.2 KW
MIT LL	112 SX STANDOFF	8 BRANCH CIRCUITS 14 IN SERIES x 8 IN PARALLEL	7.0 KW
CARLISLE	126 SX STANDOFF	9 BRANCH CIRCUITS 14 IN SERIES x 9 IN PARALLEL	7.8 KW

MIT-LL Prototype — NE RES

- 120 MODULES (BLUE FRAME)
- EACH MODULE WAS FLASHED AND HI-POT TESTED AT 1500 VOLTS DC

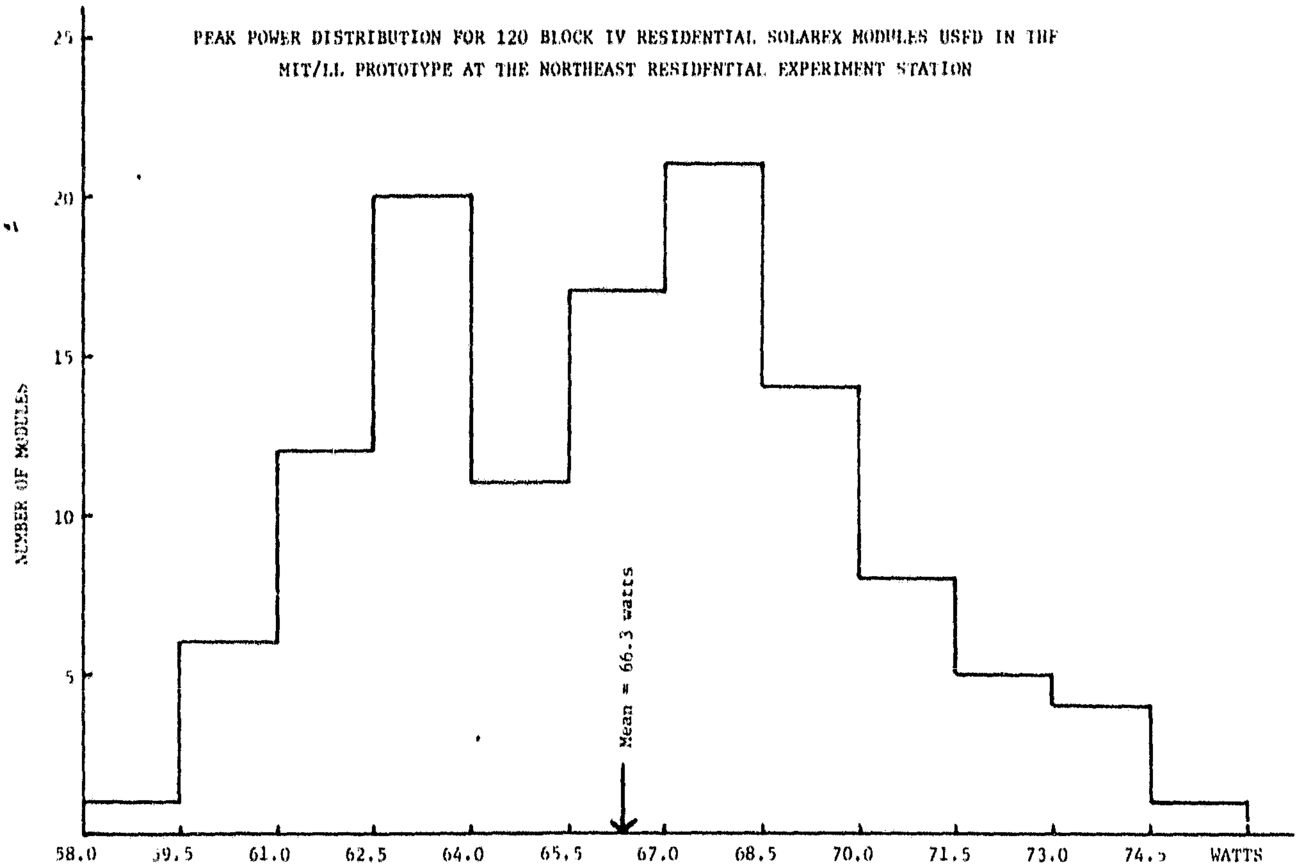
--VENDOR RATED POWER - 62.6 WATTS (100 MW/CM^2, 28°C)

--LL MEASURED POWER (AVG) - 66.3 WATTS (100 MW/CM^2, 28°C)

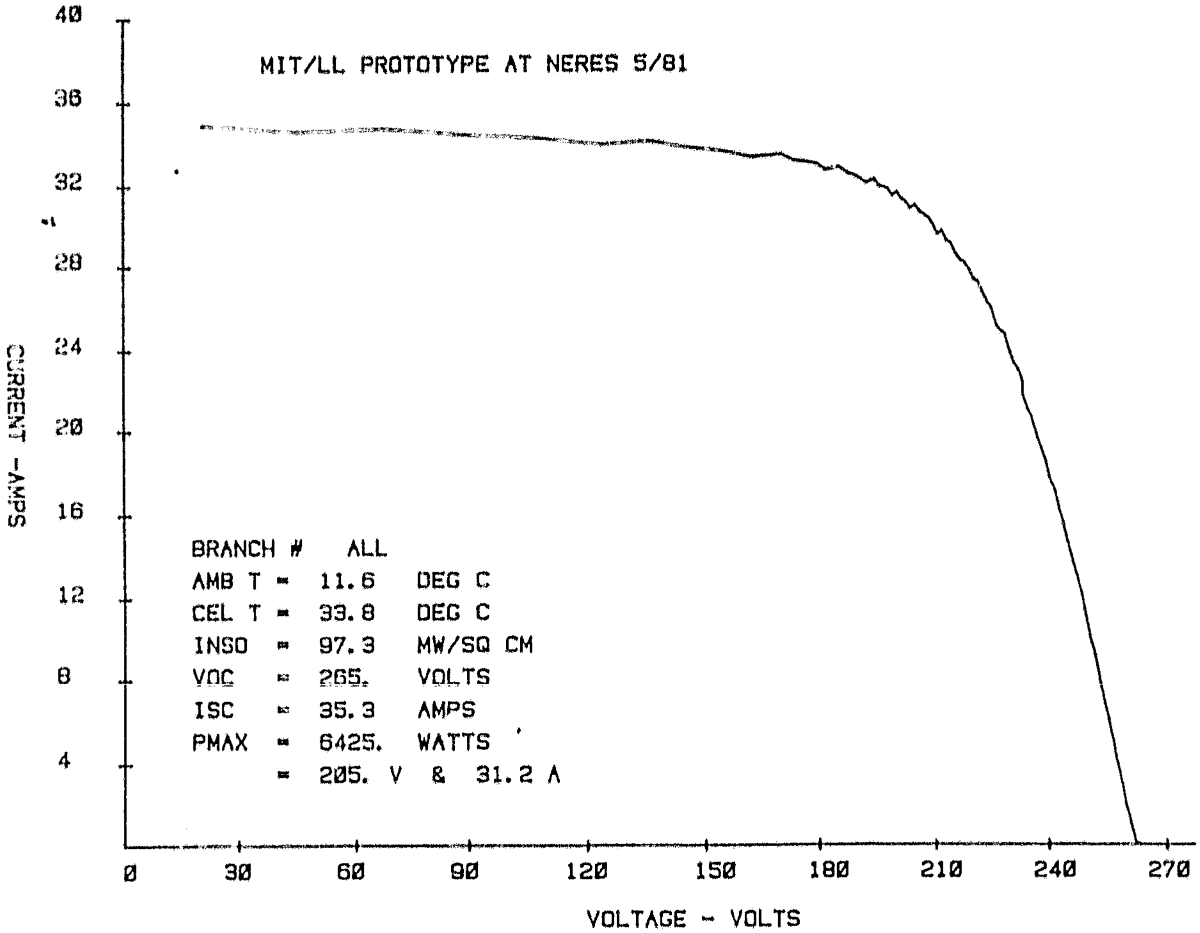
HIGH MODULE 75.3 WATTS

LOW MODULE 58.5 WATTS

--ONE MODULE FAILED THE HI-POT TEST AND WAS REPLACED


PEAK POWER DISTRIBUTION FOR 120 BLOCK IV RESIDENTIAL SOLAREX MODULES USED IN THE MIT/LL PROTOTYPE AT THE NORTHEAST RESIDENTIAL EXPERIMENT STATION
NUMBER OF MODULES
25
20
15
10
5
Mean = 66.3 watts
58.0
59.5
61.0
62.5
64.0
65.5
67.0
68.5
70.0
71.5
73.0
74.5
WATTS

MIT-LL Prototype at NE RES 5/81



MIT-LL Prototype NE RES Branch Circuit Power Characteristics

INSOLATION	96 MW/CM^2
AMBIENT TEMP	10-11°C
CELL TEMP	30-33°C

CIRCUIT	ISC	VOC	PMAX
1	4.25 AMPS	267 VOLTS	787.2 WATTS
2	4.31	268	811.2
3	4.35	268	829.6
4	4.41	265	819.9
5	4.35	266	820.4
6	4.39	266	820.4
7	4.35	264	801.9
8	4.35	266	815.8

MIT-LL Prototype NE RES Module Problems

o SINCE TURN-ON, 7 MODULES HAVE BEEN REMOVED WITH EXCESSIVE LEAKAGE CURRENT.

-- PRIOR TO INSTALLATION, THE MEASURED MODULE LEAKAGE CURRENT AT 1500 VOLTS DC WAS LESS THAN 0.1 MICROAMPS.

-- AFTER INSTALLATION, BRANCH CIRCUIT LEAKAGE CURRENTS OF AS MUCH AS 400 MICROAMPS AT THE SYSTEM OPEN CIRCUIT VOLTAGE (260-280 VOLTS) WERE MEASURED.

-- PROBLEM IS CAUSED BY MOISTURE PENETRATION INTO VOIDS IN EVA ENCAPSULANT AND SUBSEQUENT CONDUCTIVE PATHS BETWEEN CELLS BUSBARS AND METAL FRAME.

Carlisle — ISEE

- 132 MODULES (BLACK FRAME)
- EACH MODULE WAS FLASHED AND HI-POT TESTED AT 1500 VOLTS DC
  - --VENDOR RATED POWER - 62.6 WATTS (100 MW/CM^2, 28°C)
  - --LL MEASURED POWER (AVG) - 67.4 WATTS (100 MW/CM^2, 28°C)
    - HIGH MODULE 75.8 WATTS
    - LOW MODULE 56.6 WATTS
  - --TWO MODULES HAD ZERO OUTPUT AND WERE REPLACED
  - --ALL MODULES PASSED THE HI-POT TEST

PROBLEMS

o 5 MODULES WITH EXCESSIVE LEAKAGE CURRENT HAVE BEEN LOCATED AND REMOVED.

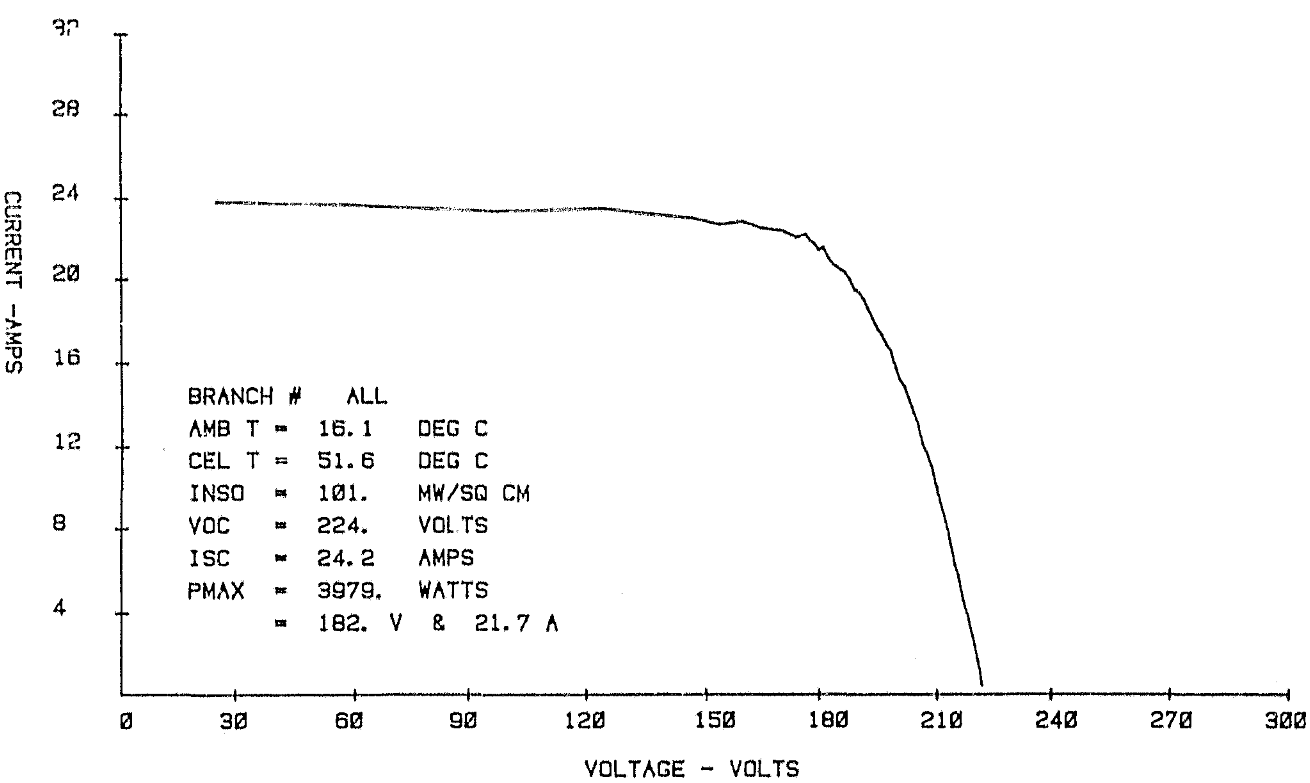
o LEAKAGE CURRENTS AS HIGH AS 2000 MICROAMPS AT THE SYSTEM VOLTAGE HAVE BEEN MEASURED.

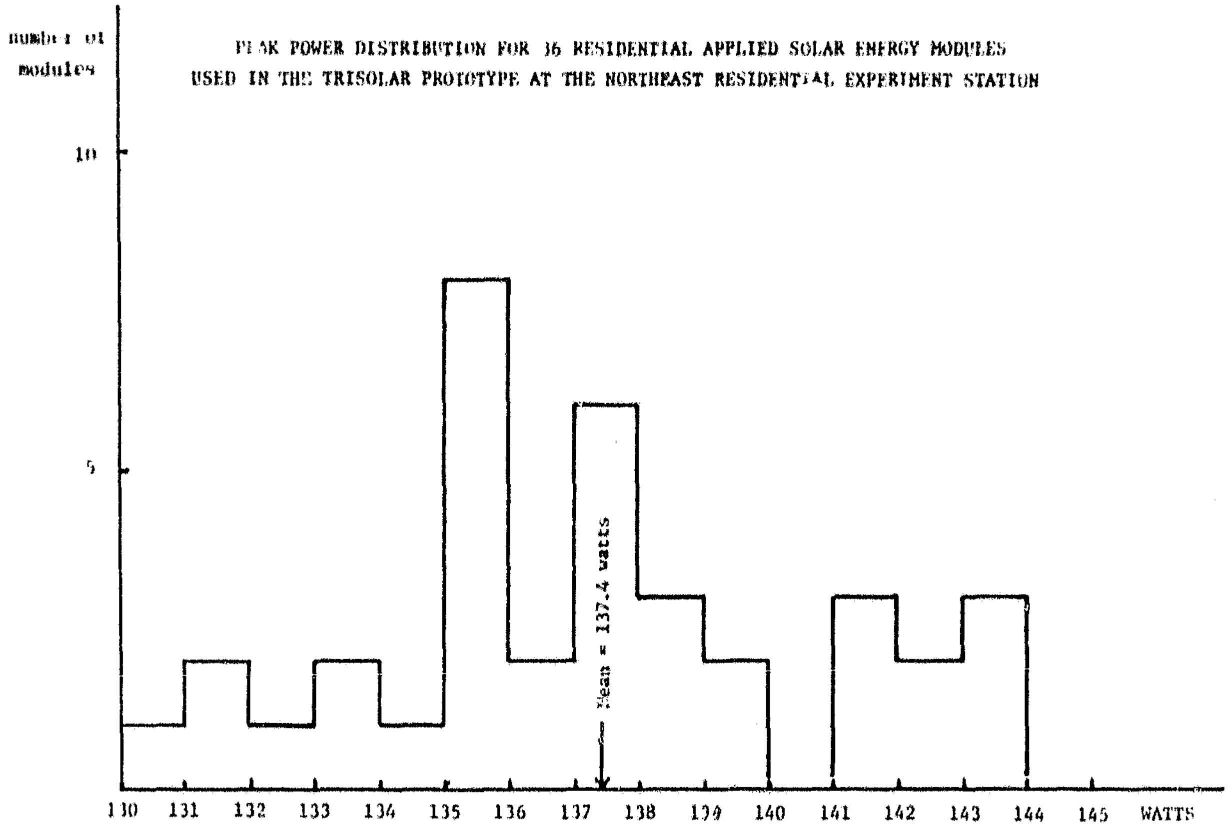
o PROBLEM IS THE SAME AS AT MIT LL PROTOTYPE AT NERES.

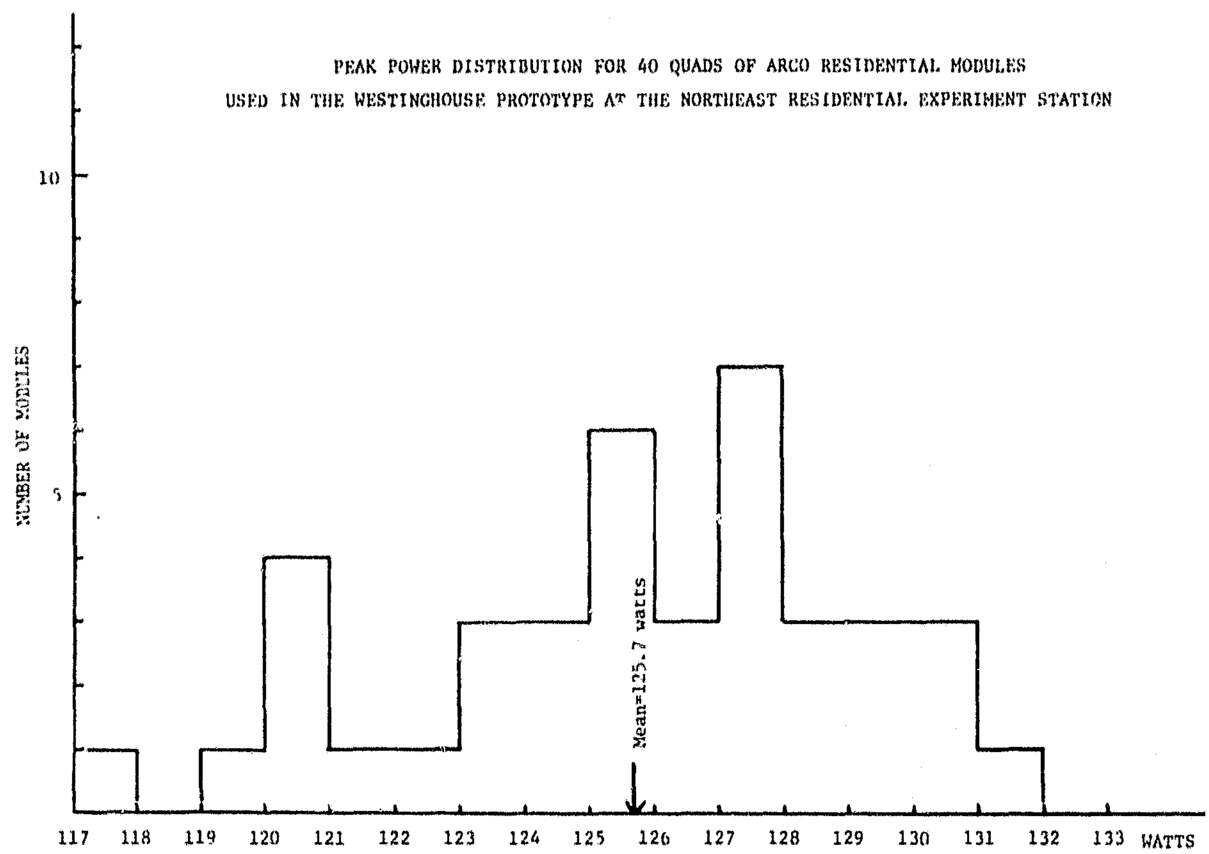
Quality Control Experience — NE RES

- IN GENERAL, MODULE PHYSICAL APPEARANCE IS GREATLY IMPROVED COMPARED TO THOSE FROM BLOCKS I, II AND III.
- MODULES WITH STIPPLED GLASS ARE DIFFICULT TO INSPECT, AS A FLUID (ALCOHOL) MUST BE SPREAD ON THE GLASS SURFACE IN ORDER TO CLEARLY VIEW CELLS THROUGH A MICROSCOPE.
- OF 252 MODULES, 32 WERE INSPECTED AT LL, WITH THE FOLLOWING OBSERVATIONS:
    1. SOLDER USAGE WAS SPARSE ON MOST INTERCONNECTS.
    2. THERE WAS AN AMPLE NUMBER OF TWISTED AND DISTORTED INTERCONNECTS. MANY WERE VERY SHORT.
    3. SOME INTERCONNECTS WERE CRACKED, ONE WAS MISSING.
    4. THE STIPPLED GLASS WAS REVERSED, MATTED FINISH DOWN, ON MANY MODULES.
    5. SOME MODULES HAD TOUCHING CELLS.
    6. VERY FEW CRACKED CELLS WERE FOUND.

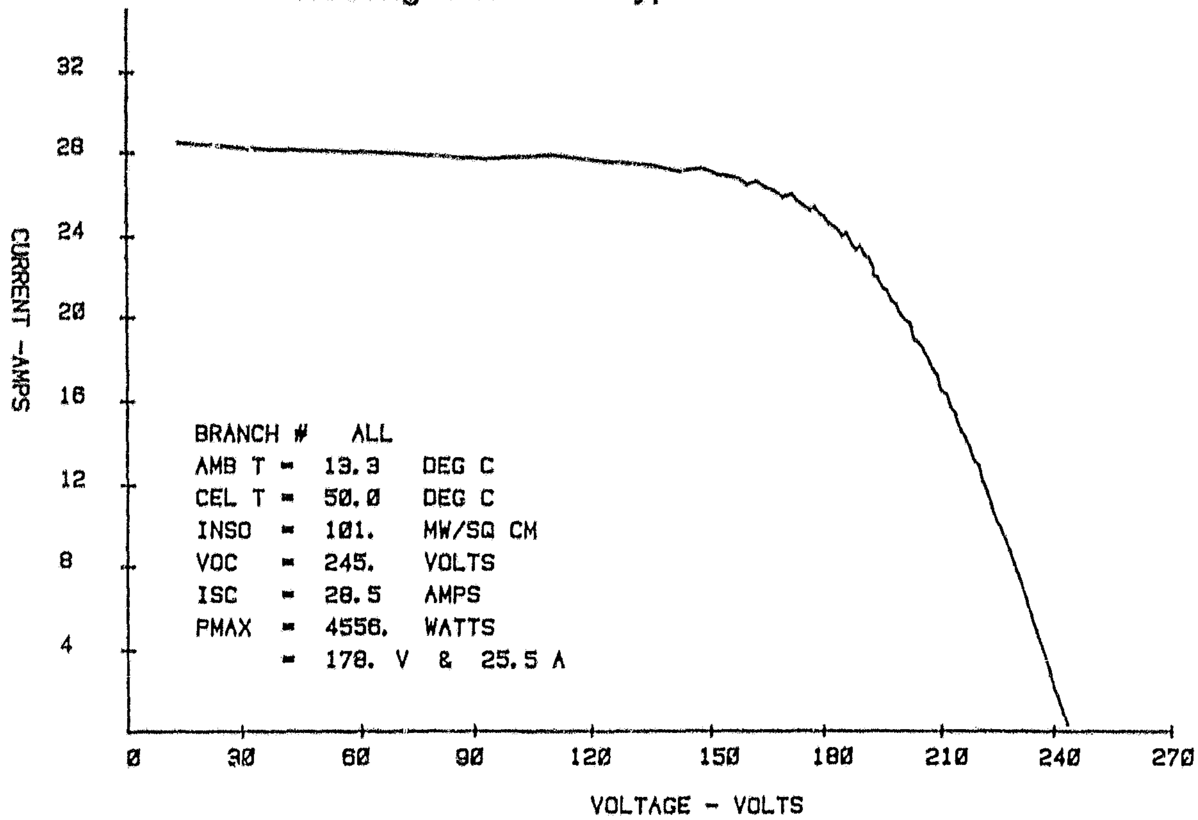
TriSolar Prototype at NE RES 5/81




number of modules
PEAK POWER DISTRIBUTION FOR 36 RESIDENTIAL APPLIED SOLAR ENERGY MODULES
USED IN THE TRISOLAR PROTOTYPE AT THE NORTHEAST RESIDENTIAL EXPERIMENT STATION
10
5
Mean = 137.4 watts
130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 WATTS


PEAK POWER DISTRIBUTION FOR 40 QUADS OF ARCO RESIDENTIAL MODULES
USED IN THE WESTINGHOUSE PROTOTYPE AT THE NORTHEAST RESIDENTIAL EXPERIMENT STATION
NUMBER OF MODULES
10
5
Mean=125.7 watts
117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 WATTS

Westinghouse Prototype NE RES 5/81



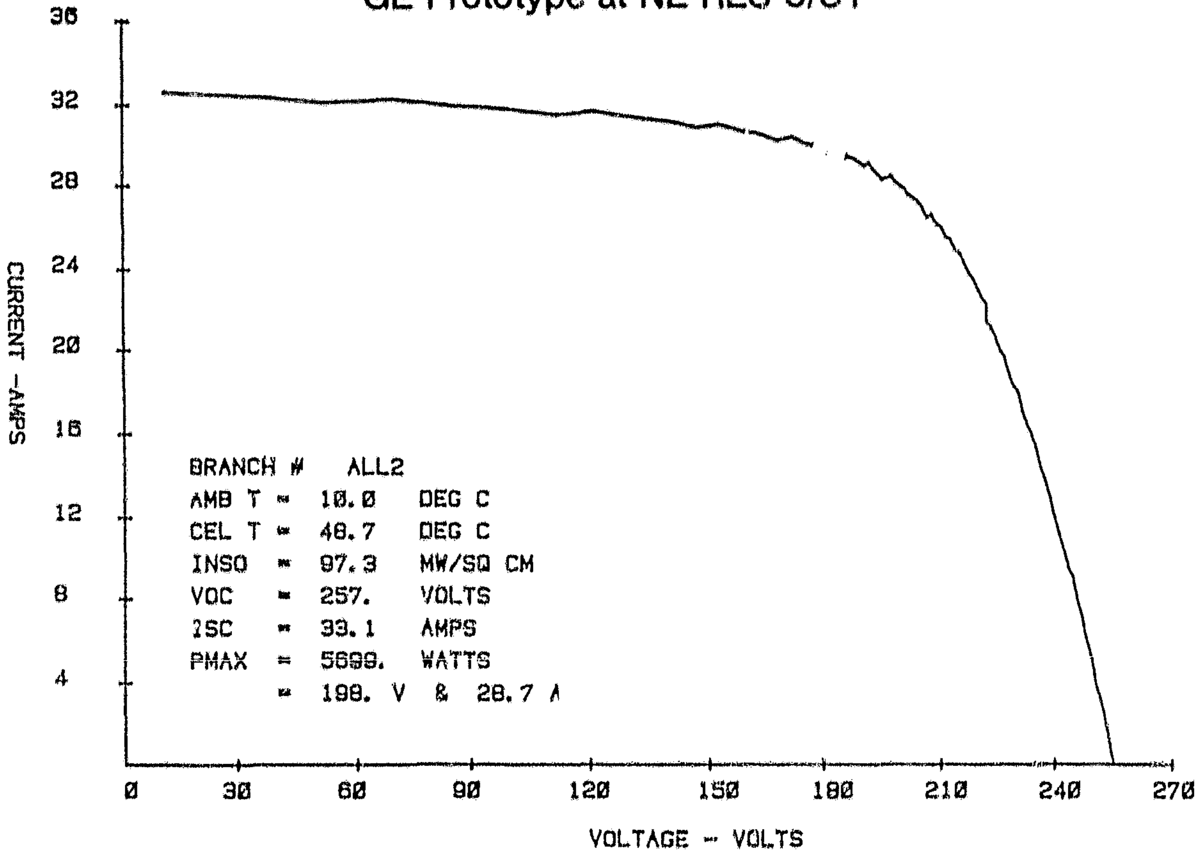
PARALLEL GROUPING POWER CHARACTERISTICS

INSOLATION--101 MW/CM^2 TAMB--12-15°C

TCELL--48-50°C

GROUPING	ISC	VOC	PMAX
1	28.2 AMPS	18.9 VOLTS	350.9 WATTS
2	28.3	18.9	358.4
3	28.7	19.1	365.9
4	28.2	19.0	358.4
5	28.3	18.9	360.9
6	28.7	18.9	365.8
7	28.7	18.9	363.4
8	28.7	18.9	355.8
9	28.2	18.9	355.9
10	28.2	18.9	353.4
11	28.3	19.0	358.4
12	27.7	18.8	341.1
13	28.0	18.8	341.2

GE Prototype at NE RES 5/81



NE RES Module Temperature Study

PROTOTYPE	MODULE MOUNTING	INSOLATION MW/CM^2	AMBIENT TEMP °C	CELL TEMP °C
MIT LL	SX STAND-OFF	97.3	11.6	33.8
TRISOLAR	ASEC INTEGRAL	101	16.1	51.6
WESTINGHOUSE	ARCO INTEGRAL	101	13.3	50.0
GE	GE SHINGLE	97.3	10	48.7

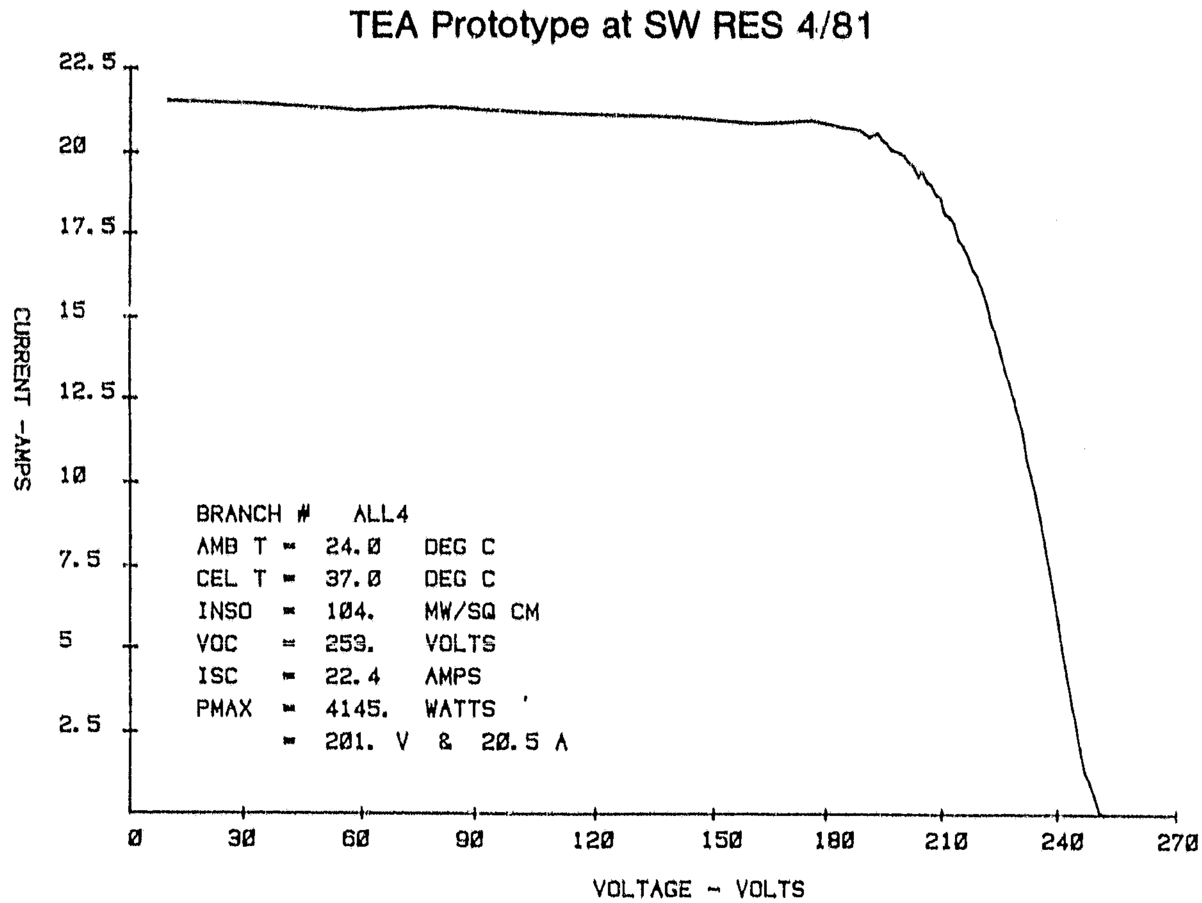
PV/T Quality Experience

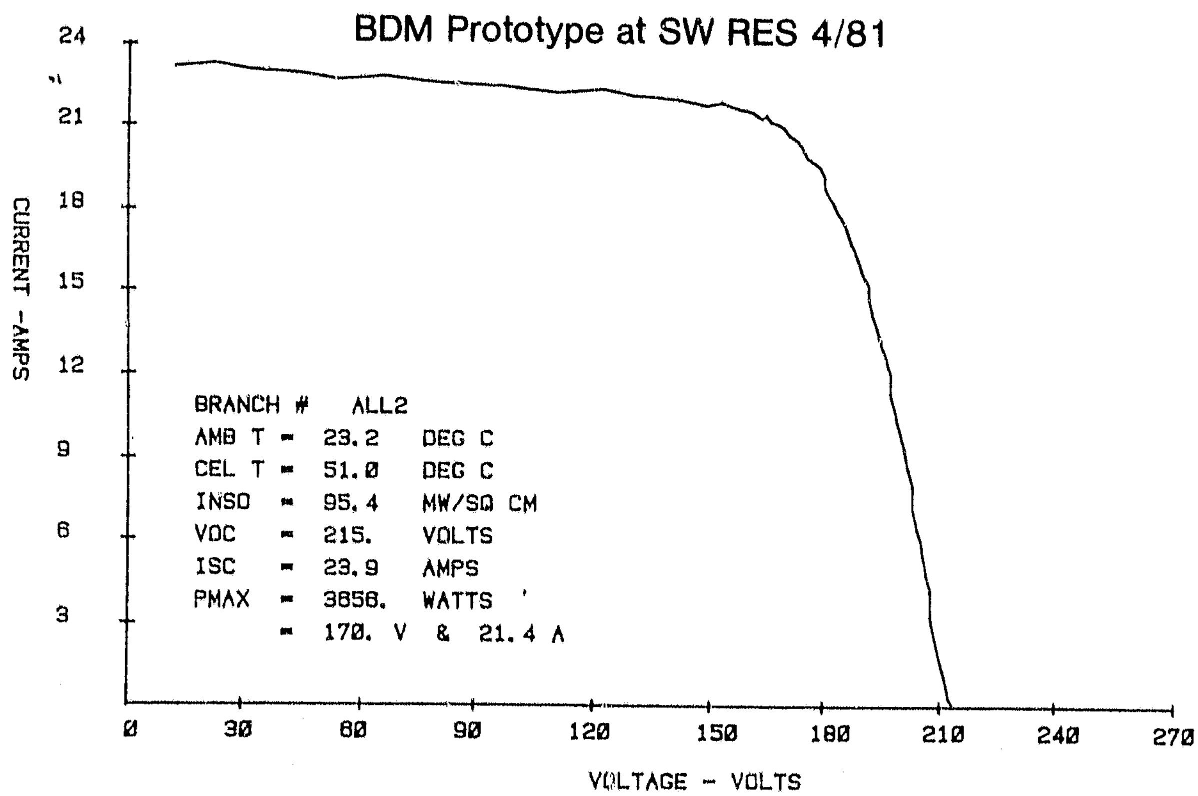
- AS IN THE CASE OF PV-ONLY MODULES, THE QUALITY OF THE PV/T MODULES INSPECTED RANGED FROM EXCELLENT TO POOR.
- VERY FEW CRACKED CELLS WERE FOUND, CONSIDERING THE NUMBER OF CELLS INVOLVED.
- THE MOST PREVALENT VISUAL ANOMALY WAS DISCOLORATION OF VARIOUS KINDS ON CELLS, INTERCONNECTS AND GRID LINES.
- ONE VENDOR HAD PROBLEMS WITH INTERCONNECT SOLDER JOINTS.

SW Residential Test Station, Las Cruces, NM

SITE OPERATOR: NMSEI

PRIME CONTRACTOR	# OF MODULES	ARRAY CIRCUITRY	RATED POWER 25°C
BDM	117 MOT STANDOFF	9 BRANCH CIRCUITS 13 IN SERIES x 9 IN PARALLEL	4.4 KW
TEA	112 MOT RACK MOUNT	8 BRANCH CIRCUITS 14 IN SERIES x 6 IN PARALLEL	4.2
SOLAREX	80 SX STANDOFF	10 BRANCH CIRCUITS 8 IN SERIES x 10 IN PARALLEL	(EST)4.8
TRISOLAR	44 ASEC INTEGRAL	2 IN PARALLEL BY 22 IN SERIES	5.2
ARTU	144 ARCO STANDOFF	12 BRANCH CIRCUITS 12 IN SERIES x 12 IN PARALLEL	(EST)4.9
ARCO	130 ARCO BATTEN-SEAM	5 BRANCH CIRCUITS 26 IN SERIES x 5 IN PARALLEL	(EST)5.9
GE	375 GE . SHINGLE	15 IN PARALLEL BY 25 IN SERIES	(EST)5.6
WESTINGHOUSE	160 ARCO INTEGRAL	12 IN PARALLEL BY 13 IN SERIES	(EST)5.4

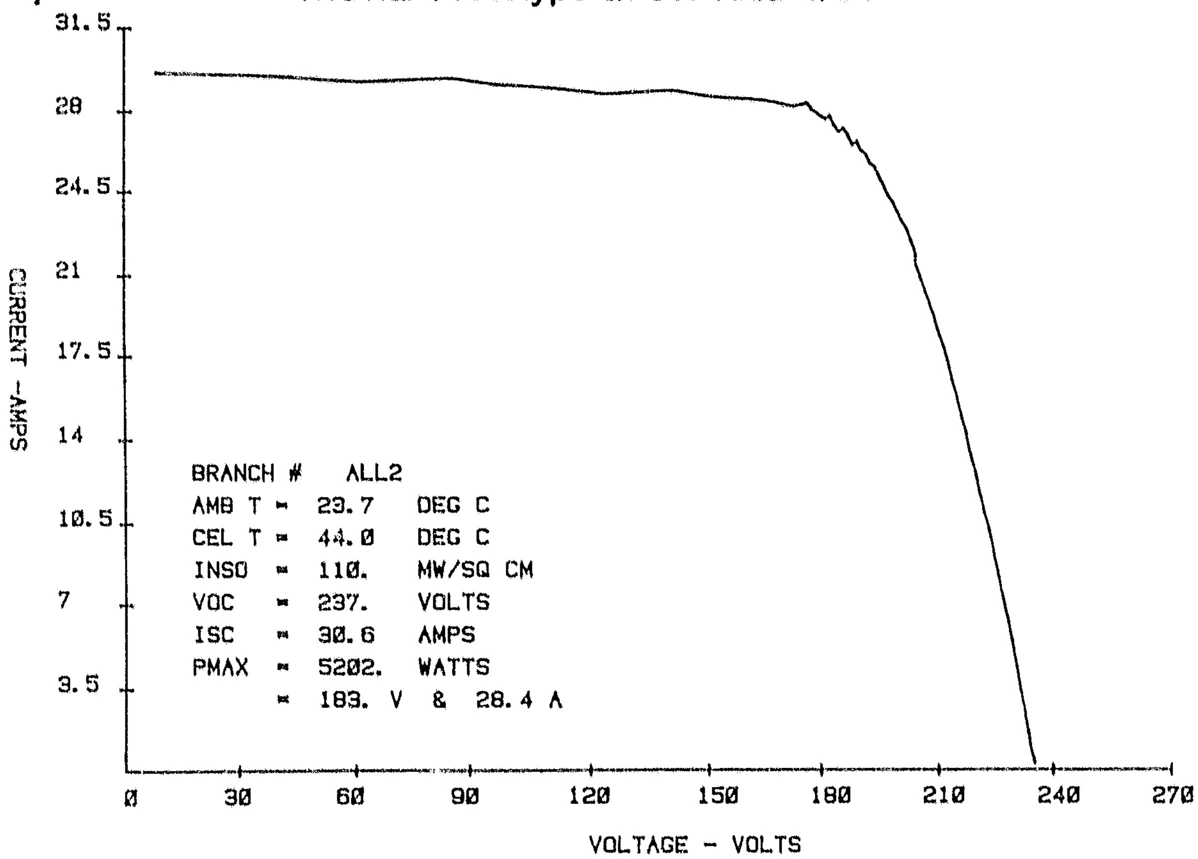

TEA Prototype at SW RES 4/81
CURRENT -AMPS
22.5
20
17.5
15
12.5
10
7.5
5
2.5
BRANCH # ALL4
AMB T = 24.0 DEG C
CEL T = 37.0 DEG C
INSO = 104. MW/SQ CM
VOC = 253. VOLTS
ISC = 22.4 AMPS
PMAX = 4145. WATTS
= 201. V & 20.5 A
0
30
60
90
120
150
180
210
240
270
VOLTAGE - VOLTS


BDM Prototype at SW RES 4/81
CURRENT -AMPS
24
21
18
15
12
9
6
3
BRANCH # ALL2
AMB T = 23.2 DEG C
CEL T = 51.0 DEG C
INSO = 95.4 MW/SQ CM
VOC = 215. VOLTS
ISC = 23.9 AMPS
PMAX = 3856. WATTS
= 170. V & 21.4 A
0
30
60
90
120
150
180
210
240
270
VOLTAGE - VOLTS

SW RES Module Temperature Study

PROTOTYPE	MODULE MOUNTING	INSOLATION MW/CM^2	AMBIENT TEMP °C	CELL TEMP °C
BDM	MOTOROLA STAND-OFF	95.4	23.2	51.0
TEA	MOTOROLA RACK MOUNT	104	24	37

TriSolar Prototype at SW RES 4/81



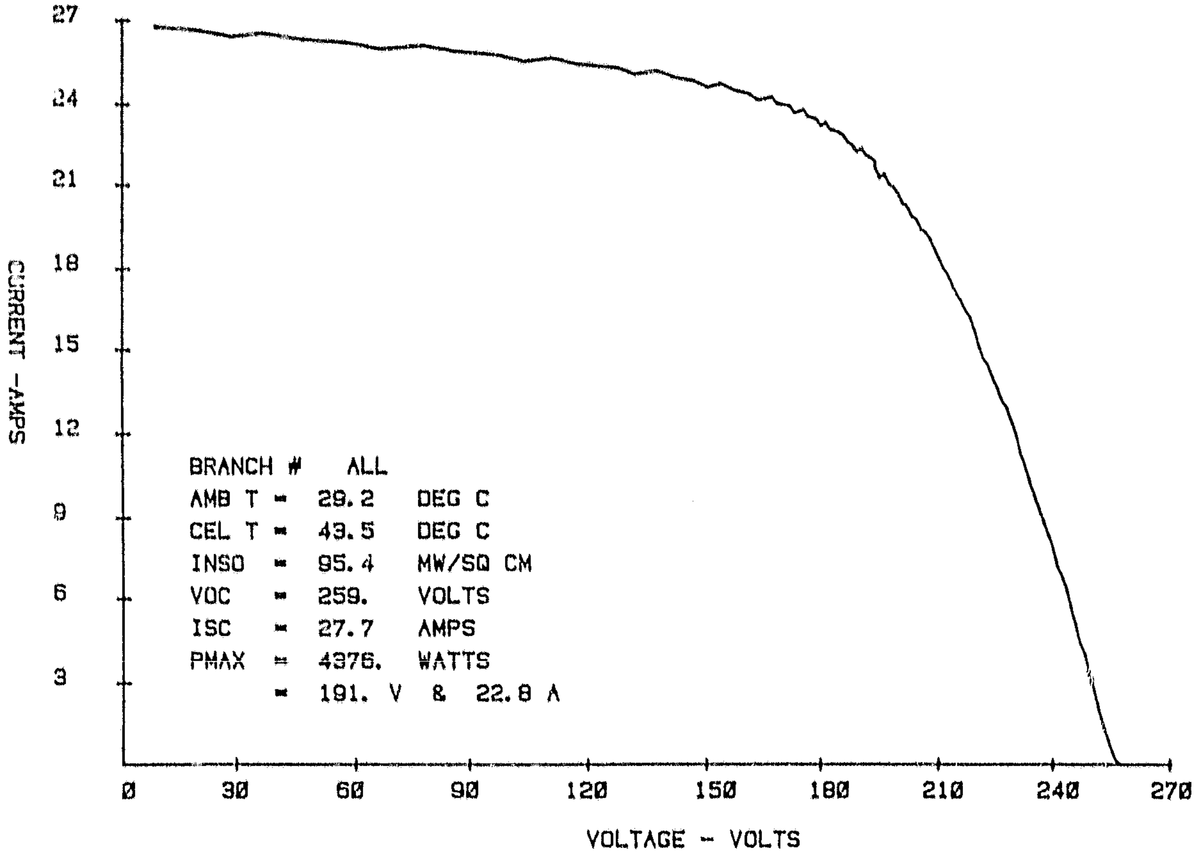
Preproduction Module Quality Control Experience, NE RES and SW RES

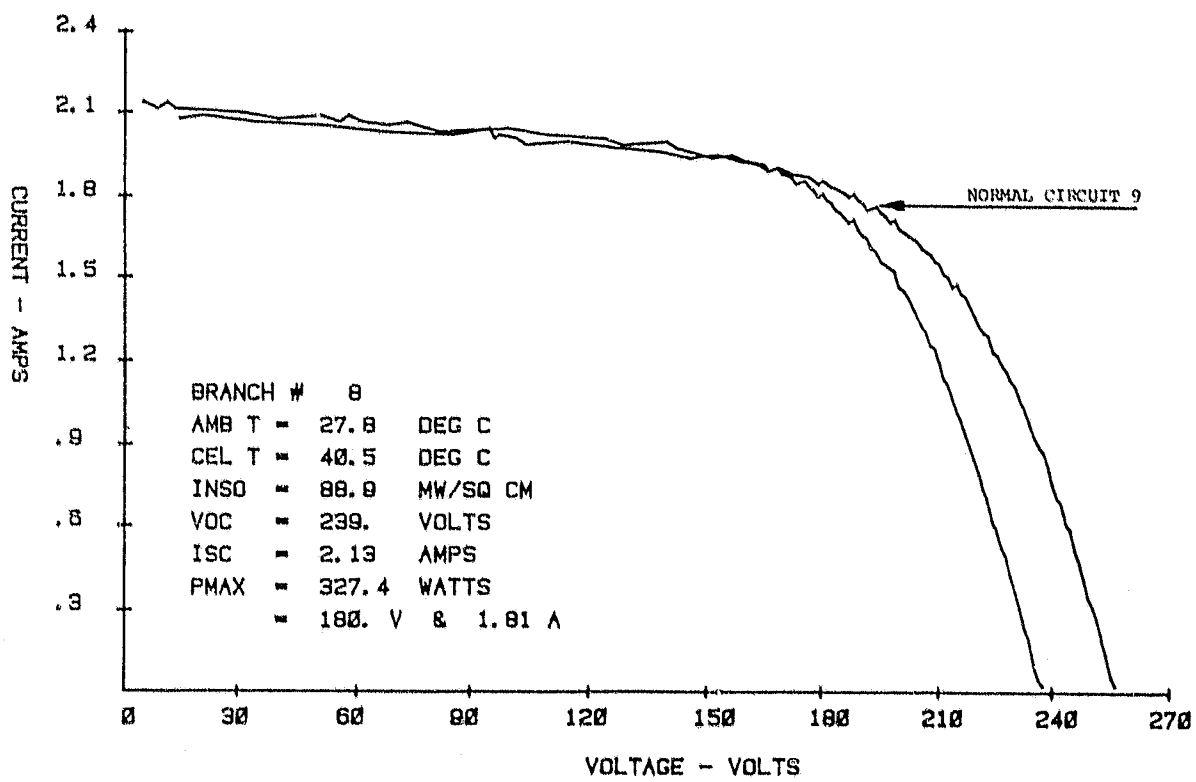
- THE VISUAL QUALITY OF THE PREPRODUCTION MODULES RECEIVED RANGED FROM EXCELLENT TO POOR.
- THE MOST OBVIOUS VISUAL ANOMALY WAS THE CRACKED CELL. EACH VENDOR SUFFERED ONE OR MORE OF THESE OF THE LOTS RECEIVED. CRACK TOLERANT CIRCUITRY WITHIN THE MODULES NEUTRALIZES THE PRESENCE OF CRACKS IN MOST CASES.
- ON TWO 60 CELL MODULES, FROM ONE VENDOR, 24 AND 10 CELLS WERE FOUND TO BE CRACKED. NO DESIGN IS THAT CRACK TOLERANT!

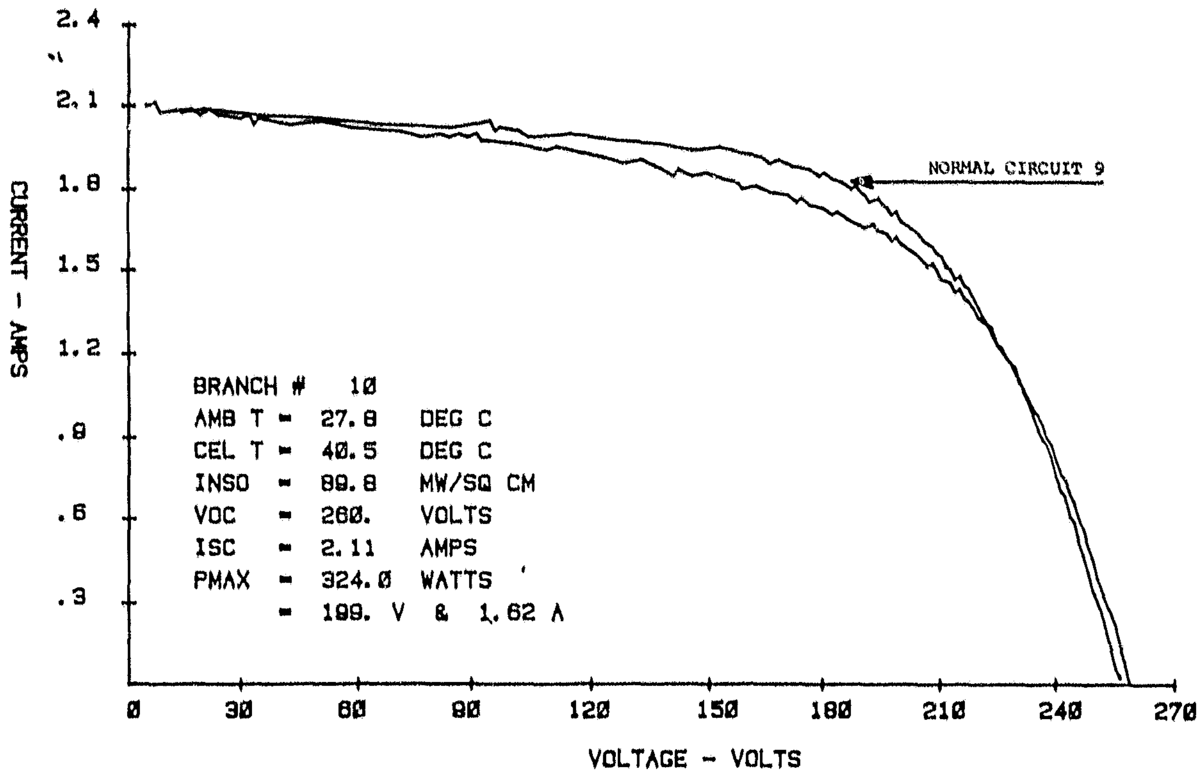
Innovative PV Applications for Residences

SITE	# OF MODULES	ARRAY CIRCUITRY	RATED POWER 25°C
JOHN LONG HOUSE-PHOENIX	120 ARCO BATTEN-SEAM	5 BRANCH CIRCUITS 24 IN SERIES x 5 IN PARALLEL	7.5 KW
FLORIDA SOLAR ENERGY CENTER	152 ARCO STANDOFF	12 BRANCH CIRCUITS 14 IN SERIES x 12 IN PARALLEL	5.0 KW
HAWAII NEI			
PEARL CITY	112 ARCO STANDOFF	8 BRANCH CIRCUITS 14 IN SERIES x 8 IN PARALLEL	4 KW
KALIHI	56 ARCO STANDOFF	4 BRANCH CIRCUITS 14 IN SERIES x 4 IN PARALLEL	2 KW
MOLOKAI	112 ARCO STANDOFF	8 BRANCH CIRCUITS 14 IN SERIES x 8 IN PARALLEL	4 KW

Florida Solar Energy Center 5/81



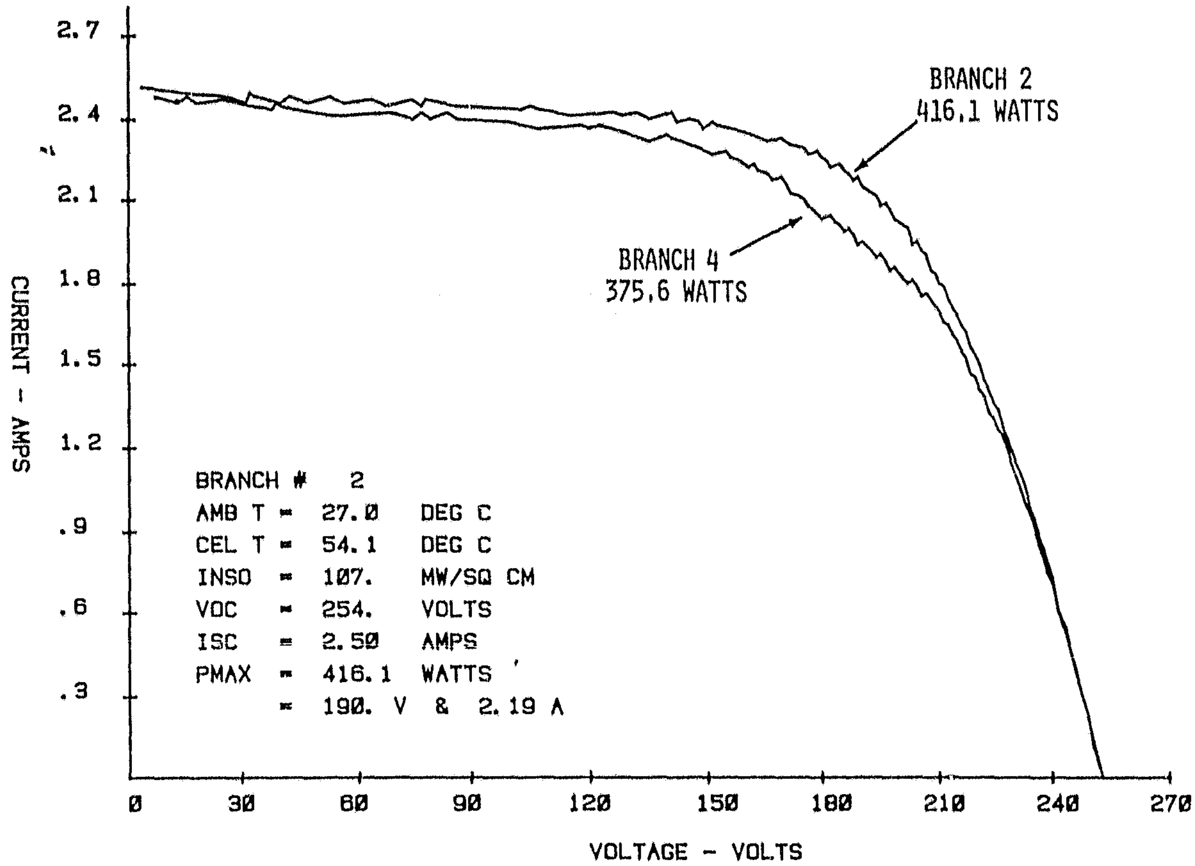




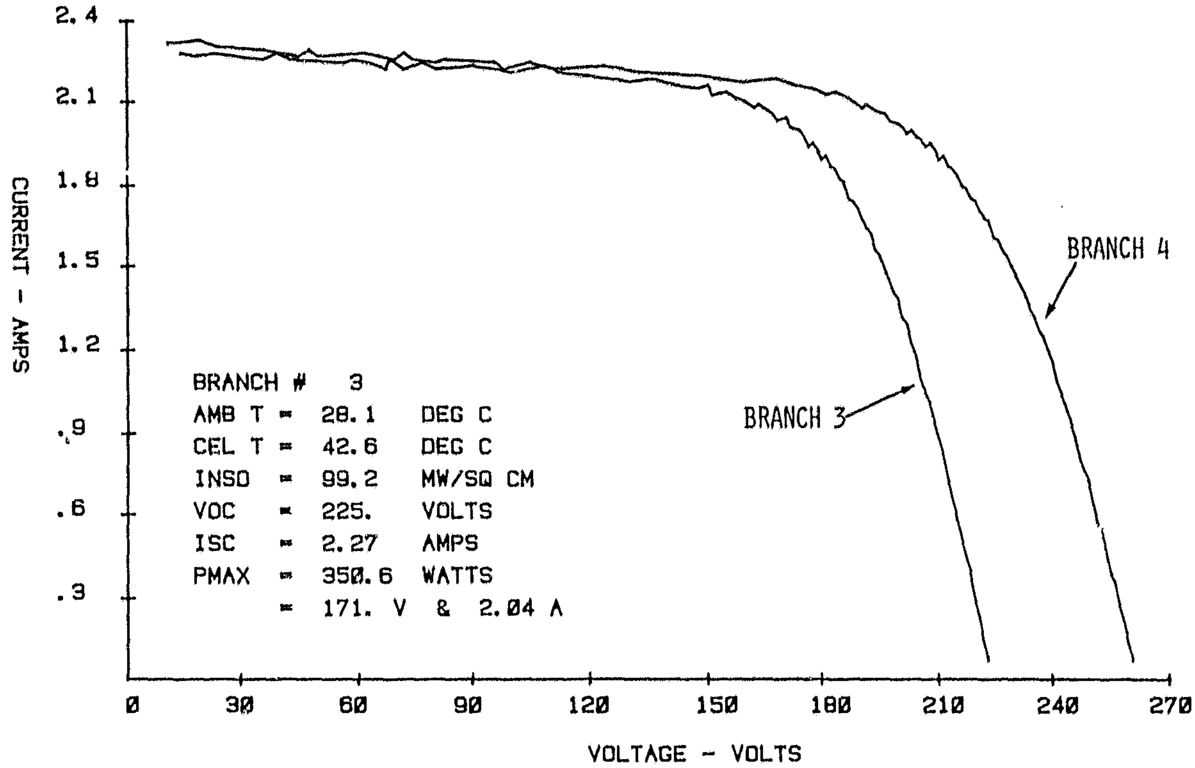
HNEI IPAR Sites

SITE	INSOLATION MW/CM2	TAMB °C	TCELL °C	VOC VOLTS	ISC AMPS	VMP VOLTS	IMP AMPS	PMAX WATTS
KALIHI	100	23	50.8	257	9.31	189	7.84	1482
PEARL CITY	100	30	55.9	259	19	195	16.4	3200
MOLOKAI	100	27.7	41.8	271	18.9	197	16.9	3350

PV Array Kalihi



PV Array Molokai House



In-Situ Visual Inspection of Modules at IPAR Sites

- OF 168 MODULES AT ONE IPAR SITE, ABOUT 1/3 WERE DELIVERED WITH CRACKED CELLS.

PERFORMANCE AND RELIABILITY OF TODAY'S MODULES

JET PROPULSION LABORATORY

L.D. Runkle

Outline

- QUALIFICATION IN AN EMERGING TECHNOLOGY
- JPL DESIGN AND TEST SPECIFICATIONS
- FIELD FAILURE EXPERIENCE
- EVOLUTION OF QUALIFICATION TEST
- FIELD OBSERVATIONS
- SIGNIFICANCE OF QUALIFICATION

Qualification in an Emerging Technology

- PROGRAM EFFECTS
- NATURE OF CRITERIA
- MODULES NOT PURCHASED BY JPL

JPL Design and Test Specifications

- CHARACTERIZATION
- QUALIFICATION
- ACCEPTANCE
- CRITERIA

Field Failure Experience

PRINCIPAL CAUSES OF MODULE FAILURE

- **CRACKED OR BROKEN CELLS**
- **FRACTURED INTERCONNECTS**
- **UNSOLDERED INTERCONNECTS**
- **GROUNDED CELL STRINGS**
- **ENCAPSULATION DELAMINATION**

APPLICATIONS EXPERIMENT MODULES

- **HOT-SPOT PROBLEM AT MT. LAGUNA**
- **FRACTURED INTERCONNECTS AT UPPER VOLTA, SCHUCHULI AND BRYAN, OHIO**
- **CRACKED COVER GLASS AT NBNM**

Qualification Test Evolution

TESTS	MODULES					TEST LEVELS
	BLOCK I	BLOCK II	BLOCK III	BLOCK IV* RES/ILC	BLOCK V* RES/ILC	
THERMAL CYCLE	100	50	50	50	200	-40°C TO +90°C, CYCLES AS INDICATED
HUMIDITY CYCLE	X	5	5	5	10	5 CYCLES AT 95% RH, 23°C TO 40°C OR 10 CYCLES AT 85% RH, -40°C TO +85°C (BLK I, 70°C AT 90% RH, 68 H)
MECHANICAL LOADING CYCLE		100	100	10000	10000	2400 N/m^2 (50 lb/ft^2) CYCLES AS INDICATED
WIND RESISTANCE				X	X	UNDERWRITERS LAB TEST NO. 997 (RESIDENTIAL ONLY)
TWIST		X	X	X	X	ONE CORNER LIFTED 2 cm/m OF LENGTH
HAIL IMPACT				20	25	10 HITS WITH ICE BALLS, DIA AS INDICATED (mm)
ELECTRICAL ISOLATION		1500	1500	1500/2000	1500/3000	50 μA MAX CURRENT AT VOLTAGE INDICATED
HOT-SPOT ENDURANCE					X	100 h SHORT CIRCUITED AT 100 mW/cm^2, NOCT

*RES: RESIDENTIAL, ILC: INTERMEDIATE LOAD CENTER

Observations From the Field

REAL-USE FAILURES OFTEN SURPRISE US

NEW MODULE FAILURE RATE IS DECLINING

QUAL TESTS ARE USEFUL IN REDUCING INFANT MORTALITY

HAILSTONES ARE A RELIABILITY DESIGN PROBLEM

NO SLOW MONOTONIC WEAROUT MECHANISM HAS BEEN OBSERVED TO CAUSE A DECREASE IN ELECTRICAL OUTPUT. TRAUMA IS THE ULTIMATE CAUSE OF MODULE FAILURE

DATA FROM JPL ENDURANCE SITES SHOWS NO OBVIOUS CORRELATION BETWEEN CLIMATE AND FAILURE RATE

Significance of Qualification

- **A NUMBER OF MODULES OF A GIVEN DESIGN HAVE BEEN SUBJECTED TO A SPECIFIED SET OF STRESS TESTS WITHOUT SUFFERING MORE THAN THE PERMISSIBLE DEGRADATION OR ALLOWABLE VISIBLE DAMAGE**
- **THE MODULES TESTED DURING JPL BLOCK PROCUREMENTS HAVE HAD SOURCE INSPECTION TO AN APPROVED PLAN**
- **THERE IS NO ASSURANCE THAT ANY SUBSEQUENT MODULE OF IDENTICAL PART NUMBER WILL PASS THE SAME TEST**

JPL FIELD TEST STRUCTURING

JET PROPULSION LABORATORY

P. Jaffe

Synopsis of Current Status

- PRIMARY FUNCTION OF THE FIELD TEST PROGRAM IS COLLECTING REAL-TIME ENDURANCE DATA
- THE ACTIVITY MAINTAINS A NETWORK OF 16 TEST SITES PROVIDING A FULL RANGE OF CLIMATIC CONDITIONS:
  - PRINCIPAL SITE AT JPL
  - 3 MEDIUM-SIZED SOUTHERN CALIFORNIA SITES
  - 12 SMALLER "CONTINENTAL" REMOTE SITES -- FROM ALASKA TO THE CANAL ZONE
- 650 PRE-1979 MODULES ARE CURRENTLY UNDER TEST AT THESE SITES -- OLDEST HAVE BEEN IN FIELD 5 YEARS, YOUNGEST 3 YEARS
- UNIQUE CHARACTERISTIC OF THE PROGRAM IS THAT EACH MODULE UNDER TEST IS <u>INDIVIDUALLY MONITORED</u>.

Reasons for Restructuring

- IMPENDING DEPLOYMENT OF A LARGE QUANTITY OF NEW STATE-OF-THE-ART MODULES REQUIRES A REALLOCATION OF THE TEST SPACE AND/OR ENLARGEMENT OF TEST SITES
- BUDGETARY REDUCTIONS NECESSITATE A CURTAILMENT OF ACTIVITIES
- MAJORITY OF MODULES CURRENTLY UNDER TEST REPRESENT OLD DESIGN TECHNOLOGY -- CONTINUED TESTING ON A BROAD SCALE IS OF QUESTIONABLE VALUE
- DATA COLLECTED TO DATE SHOWS WEAK CORRELATION BETWEEN ELECTRICAL FAILURE AND CLIMATE -- LITTLE JUSTIFICATION TO TEST IN ALL ENVIRONMENTS
- PAST EXPERIENCE SUGGESTS THAT LARGER SAMPLES AT FEWER SITES IS PREFERABLE
- UNEXPECTED FAILURE MODES EXPERIENCED IN REAL-USE APPLICATIONS POINT TO THE DESIRABILITY OF TESTING IN ARRAY CONFIGURATIONS

Restructuring Plan Highlights

- A <u>MAJOR CHANGE IN FIELD TEST PRIORITIES</u> IS PLANNED -- EMPHASIS WILL BE SHIFTED AWAY FROM COLLECTING ENDURANCE DATA AND TOWARD EARLY DETECTION AND ANALYSIS OF MODULE PROBLEMS
- TESTING WILL BE CONSOLIDATED INTO A 5 SITE NETWORK CONSISTING OF THE 4 SOUTHERN CALIFORNIA SITES AND A NEW FLORIDA SITE
- THE 12 CONTINENTAL REMOTE SITES WILL BE DECOMMISSIONED
- 16 KW OF NEW STATE-OF-THE-ART MODULES, 6 KW IN ARRAYS, WILL BE DEPLOYED
- 2 KW OF THE OLD MODULES WILL BE RELOCATED TO AN ENLARGED GOLDSTONE SITE FOR CONTINUED TESTING
- A PORTION OF THE FIELD TEST ACTIVITY WILL BE DEVOTED TO SUPPORTING THE LEAD CENTER'S T & A ACTIVITIES
- ANALYSIS OF PROBLEMS WILL BE CENTERED AT THE JPL SITE WHERE NEW MODULE/SUBARRAY TEST CAPABILITIES ARE BEING DEVELOPED

Details

- LIFE TESTING OF THE NEW MODULES WILL BE CONDUCTED UNDER BOTH INDIVIDUAL AND ARRAY LOAD CONDITIONS:
    - 6 EACH OF 6 DIFFERENT INTERMEDIATE LOAD MODULE DESIGNS WILL BE DEPLOYED AND INDIVIDUALLY TESTED AT EACH SITE
    - 7 ARRAYS OF DIFFERENT TYPE MODULES WILL BE TESTED AT JPL
- IN NORMAL OPERATION INDIVIDUAL MODULES WILL BE RESISTIVE LOADED NEAR SHORT-CIRCUIT CURRENT -- ARRAY MODULES WILL BE SERIES WIRED AND RESISTIVE LOADED NEAR PEAK-POWER
- IV DATA WILL BE OBTAINED DAILY AT JPL ON EACH INTERMEDIATE LOAD TYPE MODULE, INCLUDING THOSE IN ARRAYS. TOTAL ARRAY I-V DATA WILL BE OBTAINED WITH A NEW ARRAY DATA LOGGER.
- REMOTE SITE I-V DATA WILL BE OBTAINED TWICE A YEAR WITH OUR MODULE PORTABLE I-V DATA LOGGER.
- DATA ON THE OLD MODULES WILL BE OBTAINED ON A AS-TIME-IS-AVAILABLE BASIS

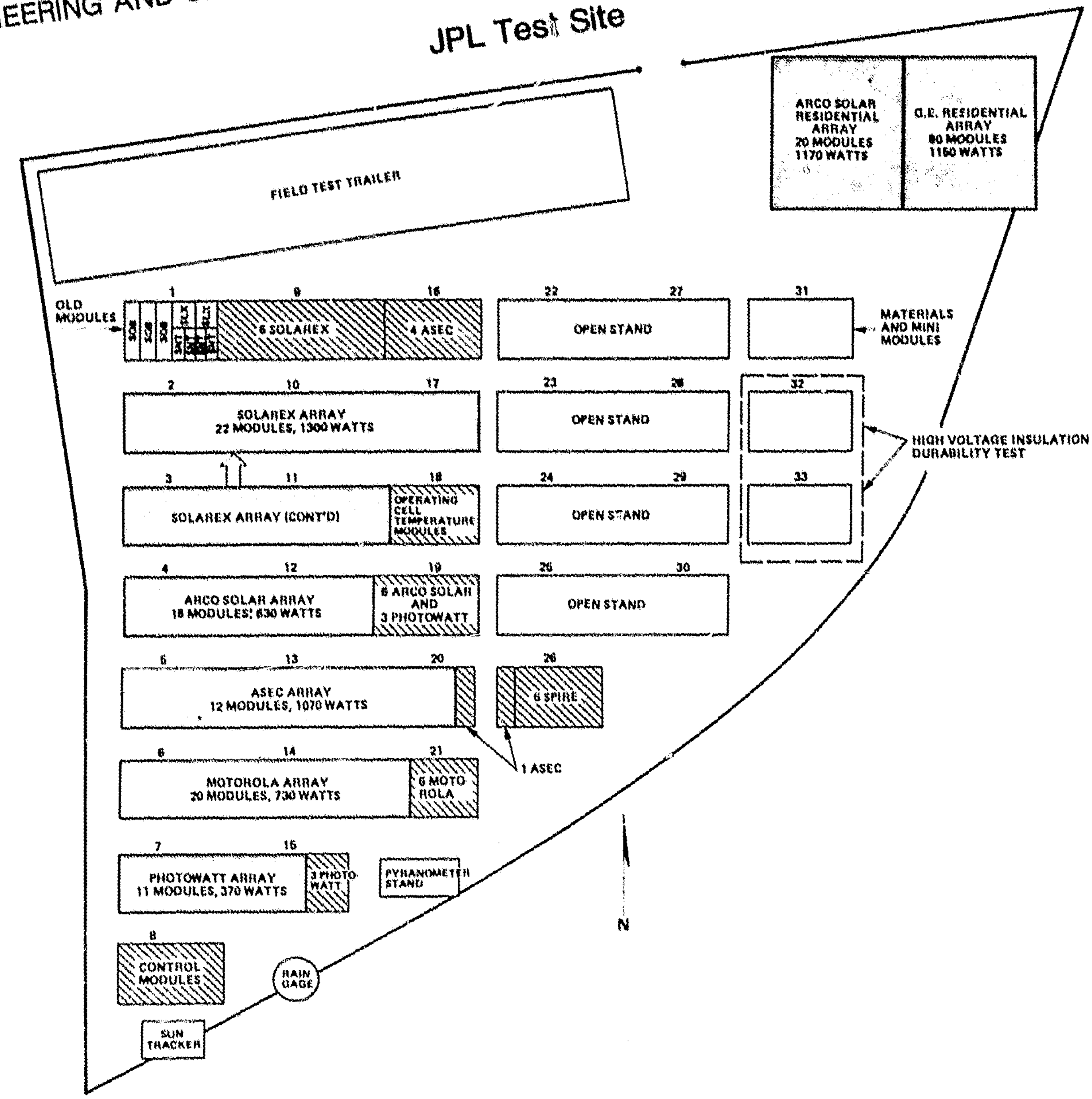
Test Modules

MANUFACTURER	TYPE	SIZE (meters)	SUPERSTATE OR TOP COVER	NOMINAL OPERATING CONDITIONS		
				V_{OC} (VOLTS)	I_{SC} (AMPS)	PEAK POWER (WATTS)
ARCO SOLAR	INT	1.22 × 0.30	GLASS	20.6	2.4	34.8
ASEC	INT	1.20 × 0.70	GLASS	19.8	6.4	89.3
MOTOROLA	INT	1.20 × 0.34	GLASS	18.8	2.5	36.4
PHOTOWATT	INT	1.20 × 0.35	GLASS	6.8	7.0	33.4
SOLAREX	INT	1.20 × 0.64	GLASS	13.4	6.8	59.0
SPIRE	INT	1.20 × 0.40	GLASS	21.5	3.6	56.6
ARCO SOLAR	RES	1.20 × 0.58	TEDLAR	10.6	6.8	53.3
G.E.	RES	HEXAGONAL, 0.48 SIDE TO SIDE	GLASS	9.3	2.4	14.4

Test Site Network

JPL/PASADENA	–	URBAN, HIGH POLLUTION ENVIRONMENT: HOT SUMMERS AND MILD WINTERS. LARGEST AND MOST THOROUGHLY INSTRUMENTED SITE. COMPUTER CONTROLLED, AUTOMATIC DATA ACQUISITION SYSTEM
GOLDSTONE	–	TYPICAL HIGH DESERT ENVIRONMENT: VERY HOT AND DRY SUMMERS, CLEAR SKIES. LOCATED NEAR BARSTOW, CALIFORNIA, AT AN ELEVATION OF 3,400 FEET
TABLE MOUNTAIN	–	TYPICAL ALPINE ENVIRONMENT: HEAVY WINTER SNOWS AND MILD SUMMERS. LOCATED IN THE SAN BERNARDINO MOUNTAINS AT AN ELEVATION OF 7,500 FEET
POINT VICENTE	–	MARINE ENVIRONMENT: DAMP MORNINGS, CLEAR AFTERNOONS, HEAVY SALT SPRAY. LOCATED ON THE PALOS VERDES PENINSULA ATOP A 100-FOOT BLUFF OVERLOOKING THE OCEAN
CAPE CANAVERAL	–	TYPICAL SOUTHEAST ENVIRONMENT: VERY HOT AND HUMID. LOCATED AT THE FLORIDA SOLAR ENERGY CENTER

JPL Test Site



Array Strings

MANUFACTURER	TYPE	NUMBER OF MODULES	NOMINAL OPERATING CONDITIONS		
			V_{OC} (VOLTS)	I_{SC} (AMPS)	PEAK POWER (WATTS)
ARCO SOLAR	INT	18	371	2.4	630
ASEC	INT	12	235	6.4	1070
MOTOROLA	INT	20	376	2.5	730
PHOTOWATT	INT	11	75	7.0	370
SOLAREX	INT	22	295	6.8	1300
ARCO SOLAR	RES	20	212	6.8	1170
G.E..	RES	80	186	9.6	1150

Goldstone Test Site

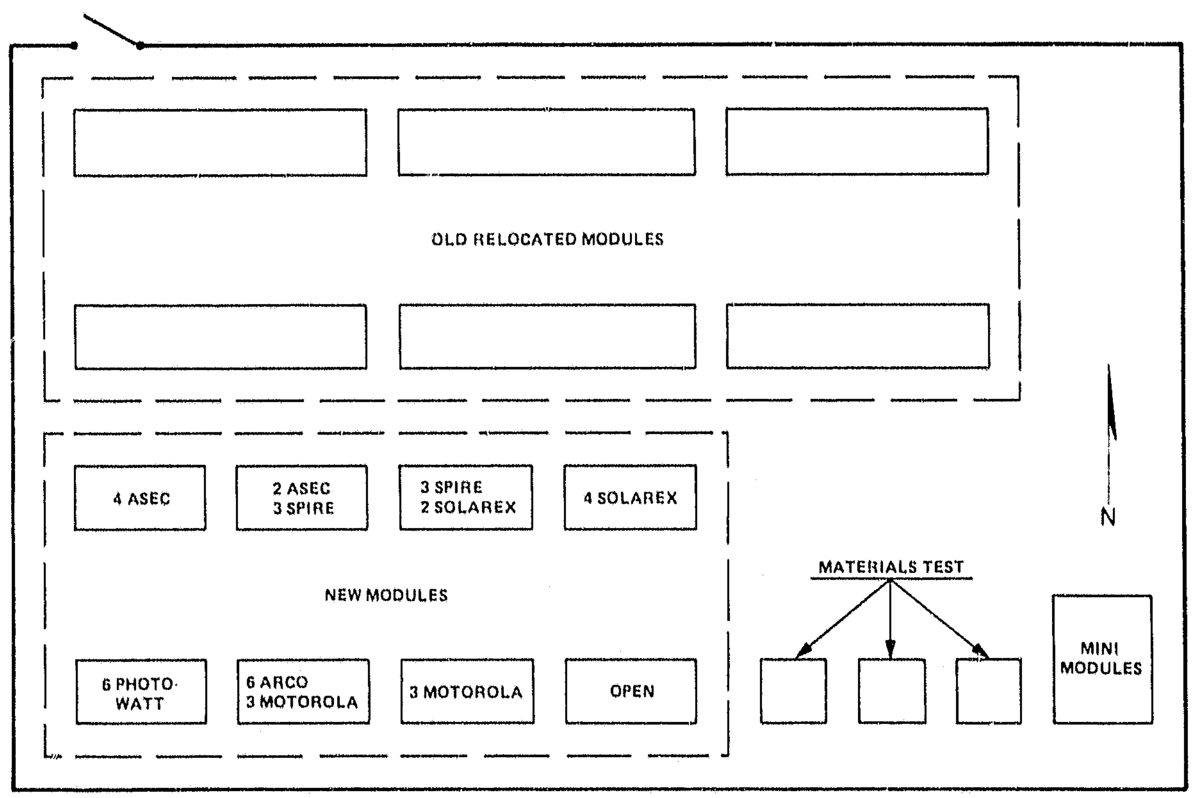
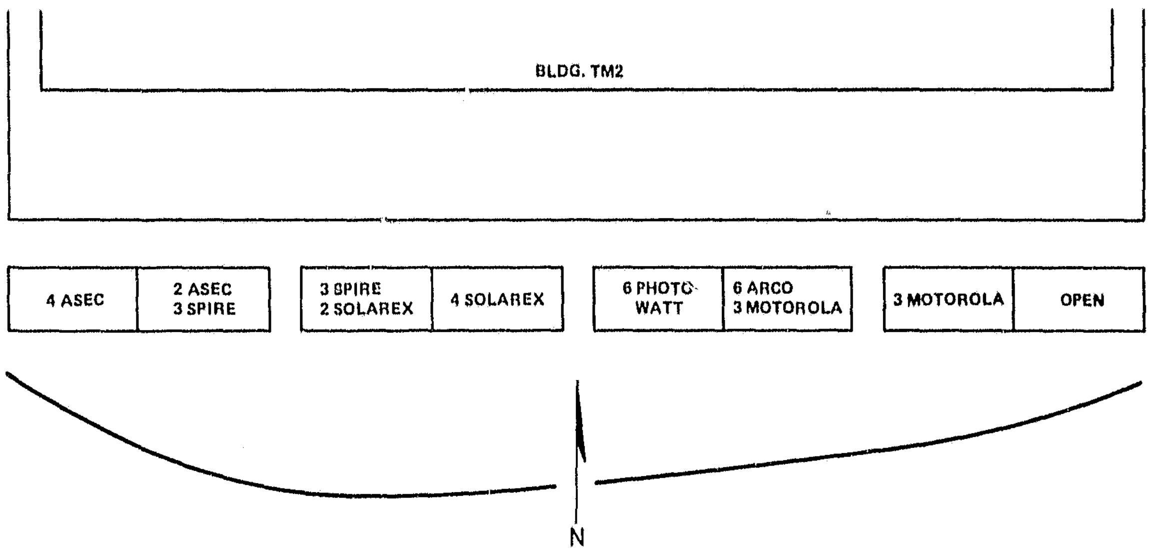


Table Mountain Test Site



Summary

- RESTRUCTURING OF THE LSA FIELD TEST ACTIVITY IS CURRENTLY GOING ON
- RESTRUCTURING SHOULD BE COMPLETE BY THE END OF SEPTEMBER
- MAIN FEATURES ARE:
  - TESTING CONSOLIDATED INTO 5 SITE NETWORK
  - THE 12 CONTINENTAL REMOTE SITES WILL BE DECOMMISSIONED
  - EMPHASIS WILL SHIFT FROM COLLECTING ENDURANCE DATA TO QUICK RESPONSE PROBLEM RECOGNITION AND ANALYSIS
  - 16 KW OF NEW STATE-OF-ART MODULES WILL BE DEPLOYED
  - 6 KW OF THESE IN ARRAY STRINGS
  - ARRAY STRINGS, IN CONJUNCTION WITH NEW ARRAY DATA LOGGER, WILL FUNCTION AS TEST BED FOR INVESTIGATION OF REAL-USE PROBLEMS

ENGINEERING AREA AND OPERATIONS AREA JOINT SESSION

NEW TEST CAPABILITIES

JET PROPULSION LABORATORY

R.W. Weaver

- THE NEW SOLAR PHOTOVOLTAIC SYSTEMS THAT ARE BEING INSTALLED HAVE A WIDE RANGE OF OPERATING CHARACTERISTICS

- DATA MUST BE OBTAINED IN ORDER TO EVALUATE PERFORMANCE AND DESIGN

- PAST EXPERIENCE INDICATES THAT FAILURE RATES INCREASE WHEN MODULES ARE SUBJECTED TO THE OPERATIONAL STRESSES FOUND IN ARRAY CONFIGURATIONS

- DETAILED DATA ARE REQUIRED TO DETERMINE EFFECTS OF ARRAY FAILURES AND ANOMALIES

- PORTABLE SOLAR ARRAY DATA ACQUISITION AND ANALYSIS SYSTEM (SADAAS)

- SOLAR ARRAY TEST FACILITY

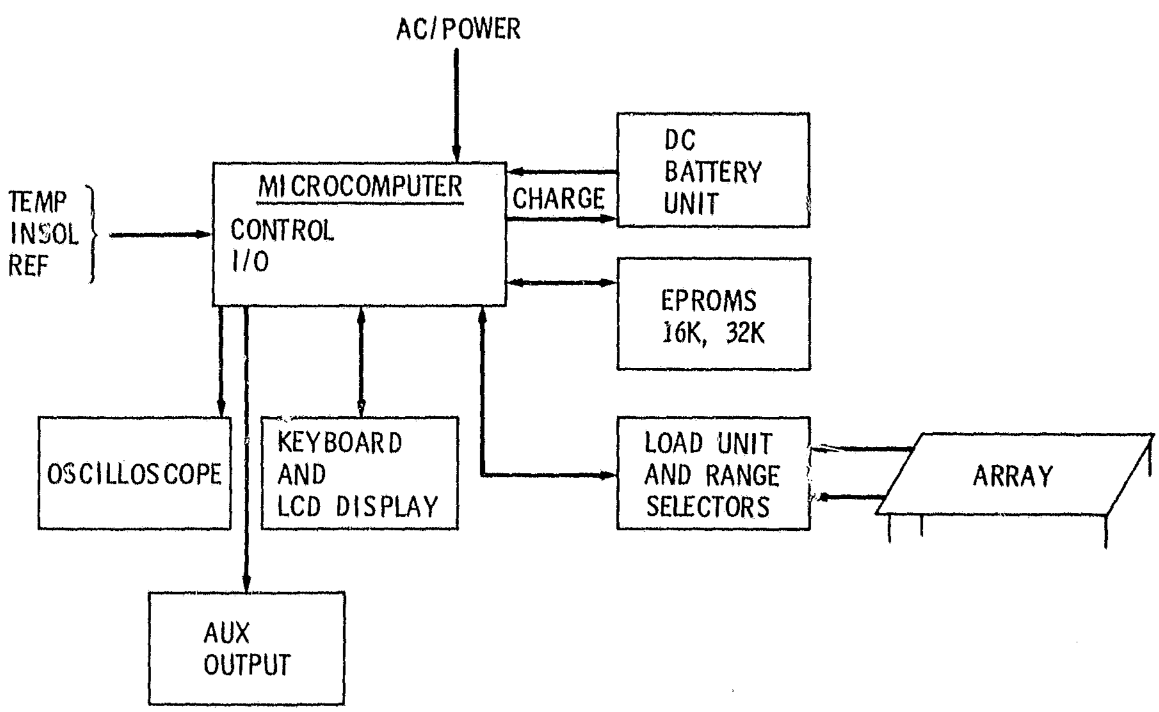
Solar Array Data Acquisition and Analysis System (SADAAS)

- REQUIREMENTS
  - VOLTAGE RANGE TO 400 VOLTS
  - CURRENT RANGE TO 40 AMPS
  - ACCEPT SIMULTANEOUS INPUTS
    INSOLATION
    TEMPERATURES
    REFERENCE CELLS
  - DATA STORAGE
    TEMPORARY
    PERMANENT
  - DATA MANIPULATION
    STANDARD PROCESS
    PROGRAMABLE
  - DISPLAY
    DIGITAL
    PLOTS
  - DATA RATE
    COMMENSURATE WITH CURRENT-VOLTAGE
    TO MINIMIZE VOLTAGE STEP SIZE
    ACQUISITION TIME OF A SECOND OR LESS

- CONSTRAINTS
  - SELF POWERED, RECHARGEABLE AND OPERABLE FROM AC LINE POWER
  - MAXIMUM CARRY WEIGHT 40 pounds PER CASE
  - MUST SURVIVE BEING CHECKED THROUGH AIRLINE BAGGAGE OR FIT UNDER SEAT

- DESIGN APPROACH
  - LOAD PATTERNED AFTER MIT/LL CAPACITIVE CHARGE TECHNIQUE WITH A BANK OF SWITCHABLE CAPACITORS
  - USE PLUG-IN EPROMS FOR DATA AND ADDITIONAL PROGRAM STORAGE
  - A PERMANENT RESIDENT PROGRAM FOR DATA ACQUISITION
  - A BASIC LANGUAGE INTERPRETER FOR OTHER PROGRAMS
  - CONTROL, INPUT AND OUTPUT VIA KEYBOARD WITH LCD DISPLAY
  - PLOTS ON OSCILLOSCOPE (BATTERY POWERED)
  - DATE RATE CONTROLLED VIA VOLTAGE-CURRENT RANGE SELECTORS WHICH CONFIGURE THE CAPACITOR BANK
  - AUXILIARY OUTPUT INTERFACE FOR HARDCOPY DATA OR PLOTS (RS-232)

Major Component Diagram



SADAAS Contd.

- MICROCOMPUTER UNIT
  - CONTROLS SYSTEM VIA KEYBOARD INPUT
  - CPU, RAM
  - CUSTOM SOFTWARE EPROM FOR DATA ACQUISITION FUNCTION
  - BASIC EPROM FOR SPECIAL PROGRAMMING
  - SELF CALIBRATING MODULE
  - INTERFACES FOR CONTROL AND I/O
  - SPECIAL OUTPUT FOR OSCILLOSCOPE
    DIGITAL TO ANALOG HIGH SPEED OUTPUT OF DATA

- LOAD UNIT
  - CAPACITOR BANK
  - RANGE SELECTION SWITCHES

V	I
400	40
200	20
100	10
50	5

    ANY COMBINATION AVAILABLE

  - ANALOG TO DIGITAL CONVERTERS
  - VOLTAGE REFERENCE
  - SCR CONTROLLED

- IT CAN GO ON AN AIRPLANE
- NO COMPONENT WEIGHS OVER 40 pounds
- SELF POWERED
- SPECIAL PROGRAMMING AVAILABLE
- DATA FROM EPROMS CAN BE FEED INTO EXISTING PDP II COMPUTER
- WILL BE READY IN SEPTEMBER

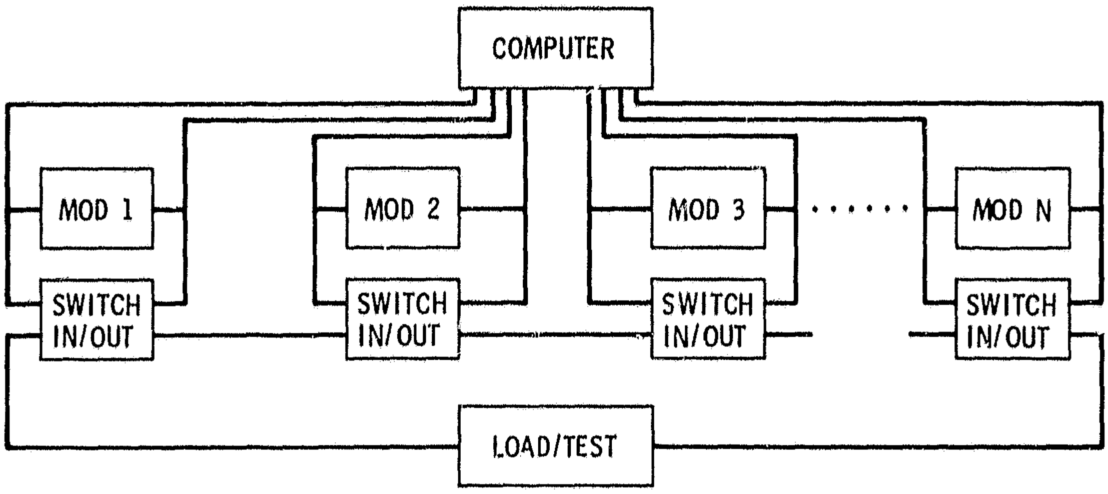
Array Simulation at the JPL Site

- OBTAIN DATA FROM ARRAYS OF LATEST TECHNOLOGY MODULES
- SIMULATE ANOMALIES AND FAILURES AND MEASURE THE EFFECTS
- VARY OPERATIONAL PARAMETERS TO DETERMINE EFFECTS
- CORRELATE OPERATIONAL DATA WITH ARRAY DATA

DATA

- INDIVIDUAL MODULE IV
- TOTAL ARRAY
- PARTIAL ARRAY
- VARYING LOAD

Typical Configuration



ARRAY RANGES

V_{OC} 75 TO 390 VOLTS

I_{SC} 2 TO 7 AMPS

MAX P 0.4 TO 1.3 KW

Summary

- EXPANDED IN FIELD TESTING
- ARRAY SIMULATION
- ANALYZE PERFORMANCE

CLEANING STUDY OF SOILED GLASS PV MODULES

JET PROPULSION LABORATORY

A. H. Wilson

- **OBJECTIVE**
  - **EFFECTIVELY CLEAN MODULE GLASS WITHOUT RUBBING OR WIPING**

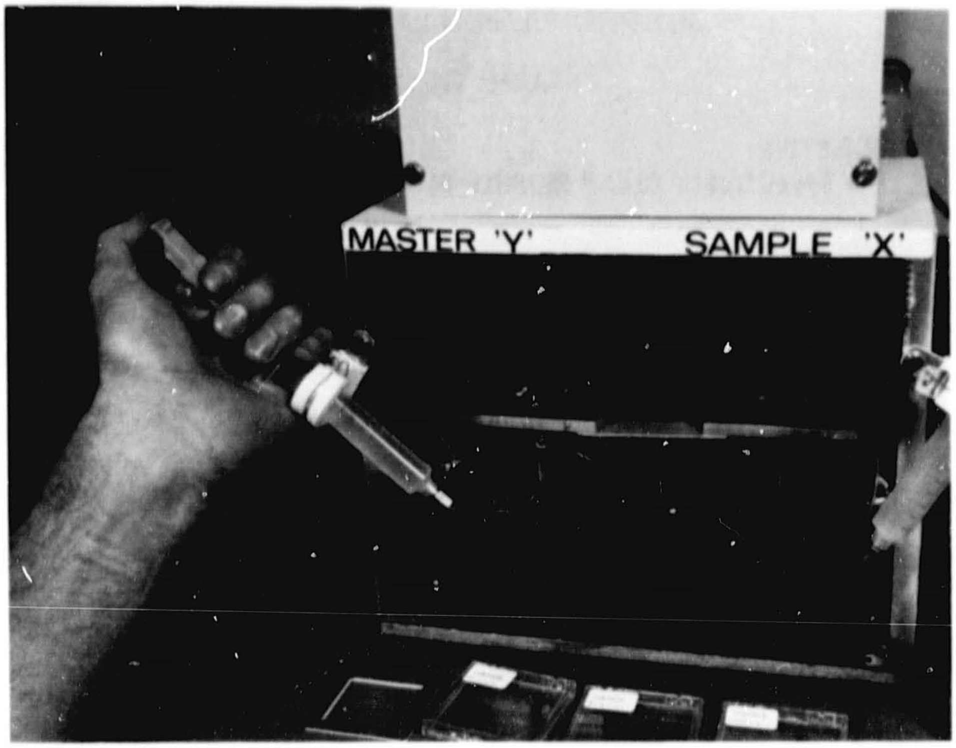
- **PROCEDURE**
  - **OBTAIN SOILED GLASS SAMPLES**
    - **FROM SITES**
    - **FROM PREPARATION IN LABORATORY**

  - **CLEAN SAMPLES**
    - **WATER WASH ONLY**
    - **COVER WITH DETERGENT FILM, THEN WATER WASH**

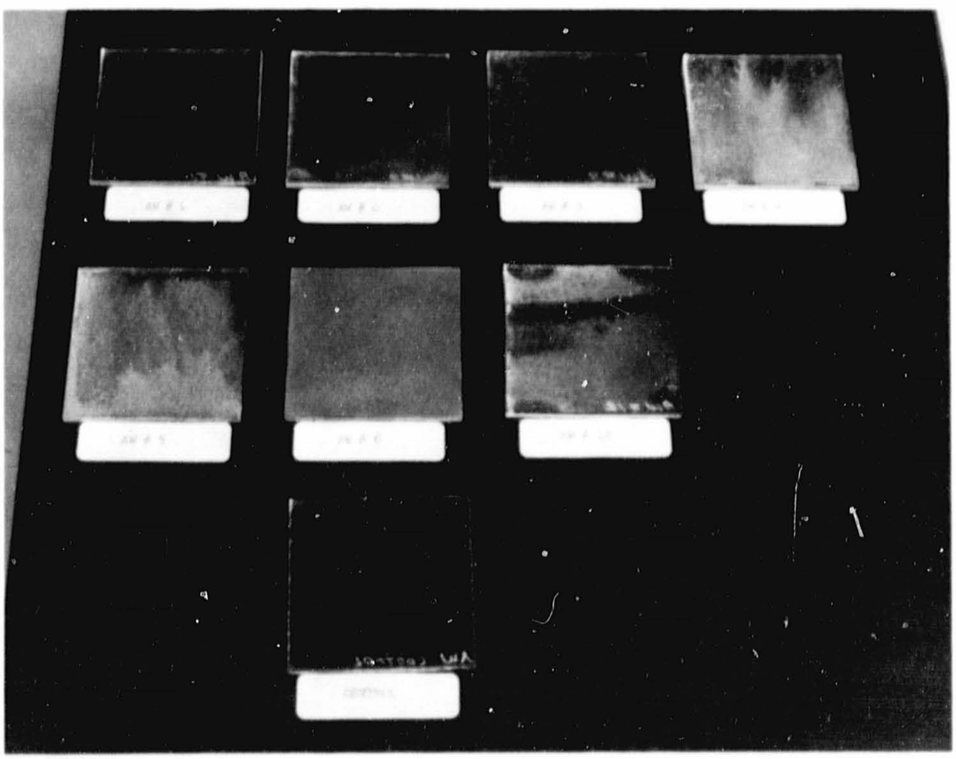
  - **MEASURE CLEANING EFFECTIVENESS**
    - **PERFORMANCE OF MODULES BEFORE AND AFTER FIELD EXPOSURE TO RAIN**
    - **TRANSMITTANCE CHANGE OF SAMPLES**
    - **VISUAL EXAMINATION**

FIELD APPLICATION FACTORS
- **LABOR**
- **DISPENSER**
- **CHEMICALS**

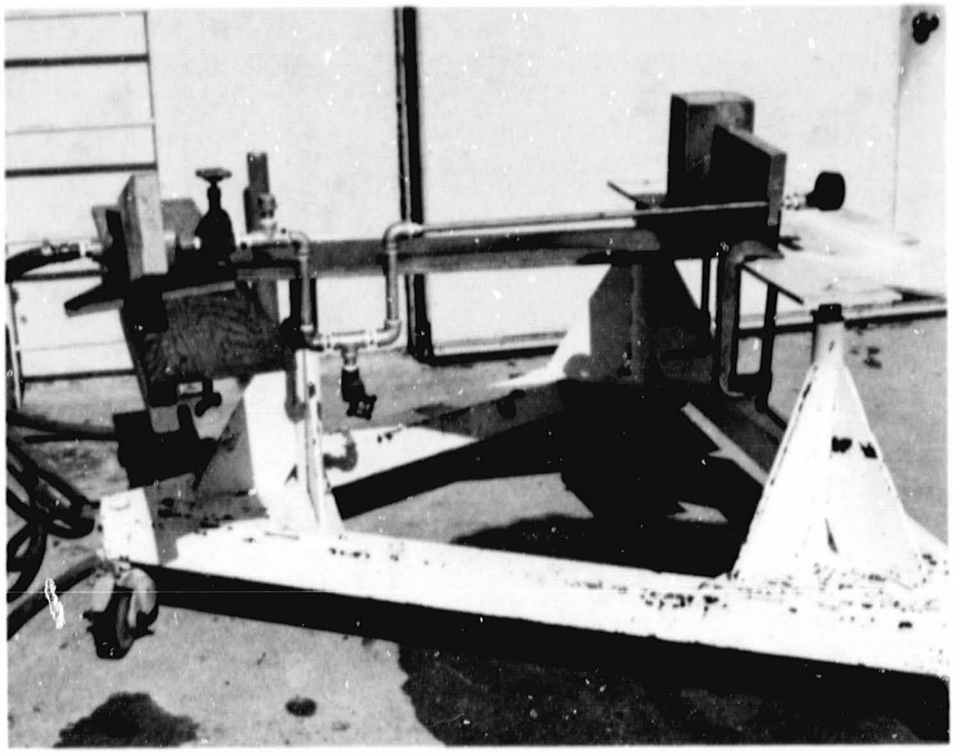
Transmittance Measuring Apparatus



Samples

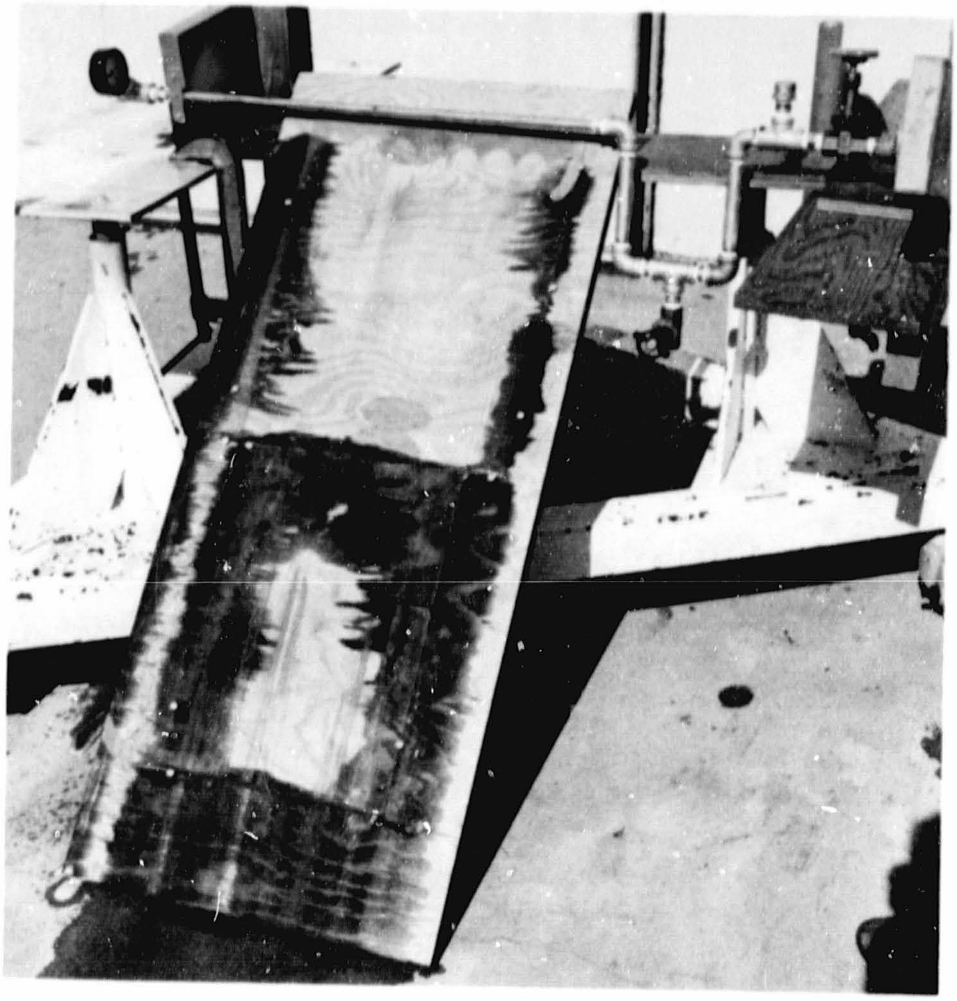


Experimental Cleaning Device

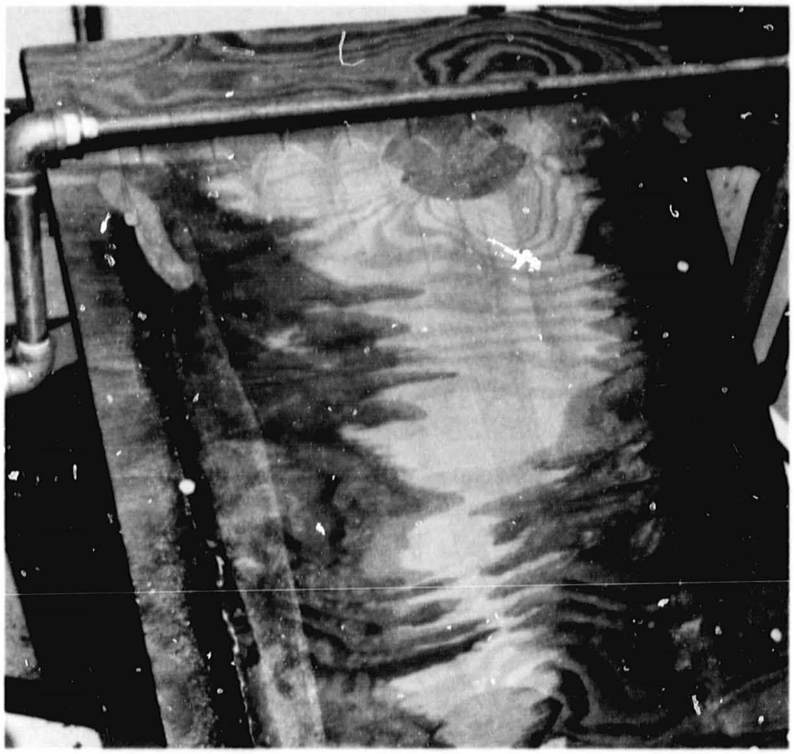


ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Experimental Cleaning Device in Operation,
Cleaning Two Glass Plates



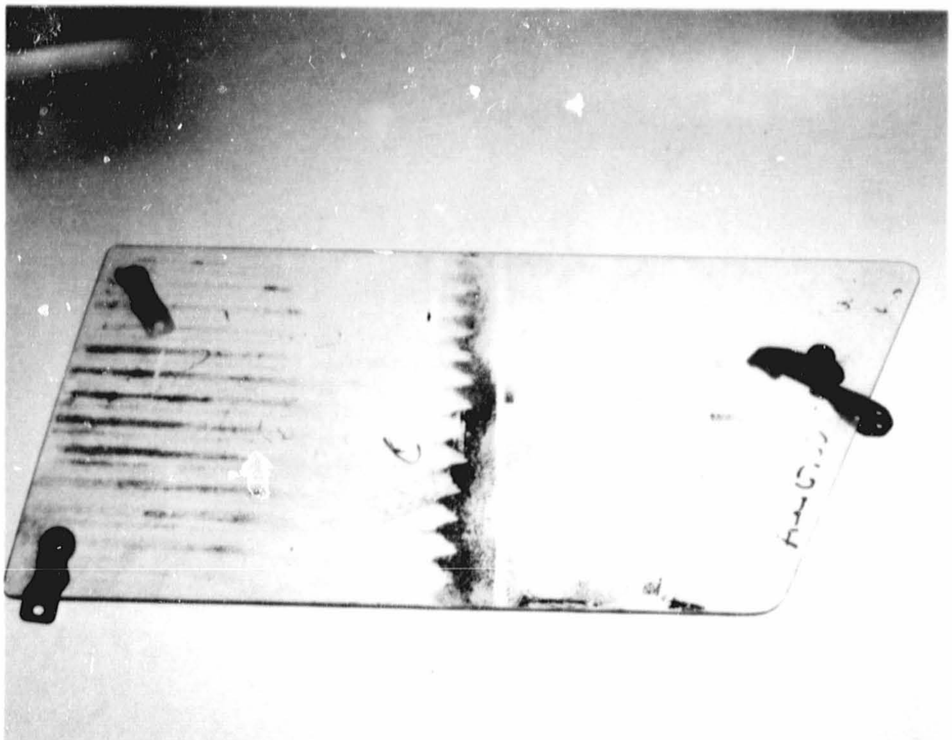
Closeup of Cleaning Tube



Upper Glass Plate After Cleaning

Lower Glass Plate After Cleaning

Various Cleaning Methods Applied to Soiled Window
(Obtained From Auto Wrecking Yard)

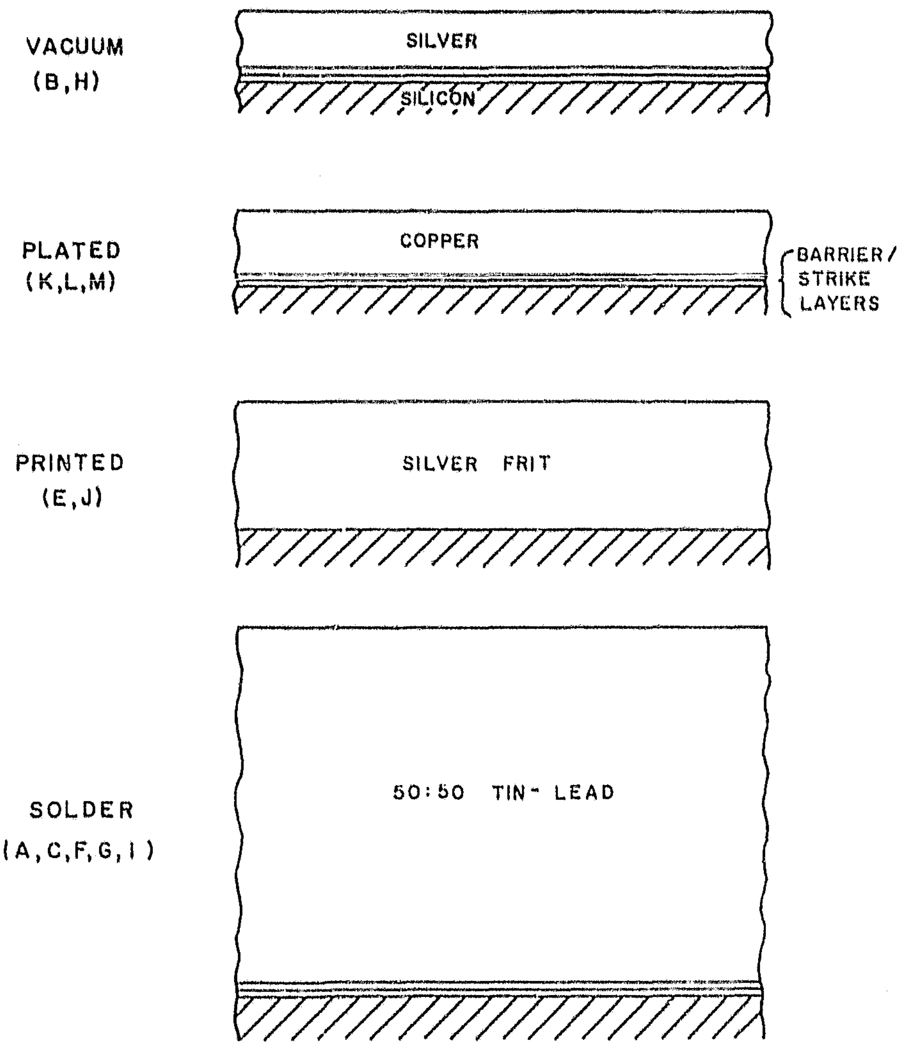


ENCAPSULATED AND UNENCAPSULATED SOLAR CELL RELIABILITY TESTING

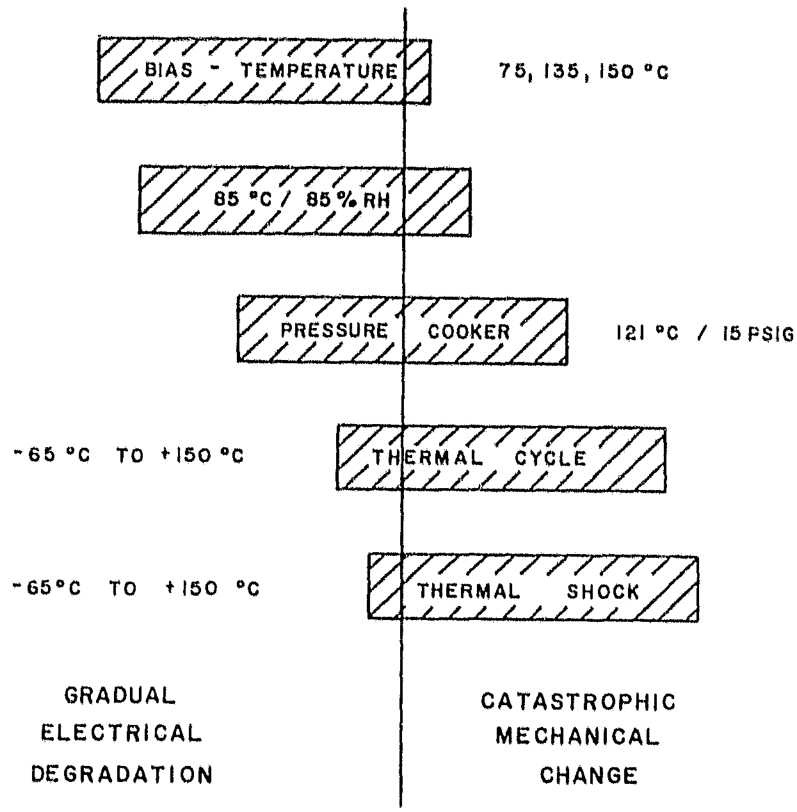
CLEMSON UNIVERSITY

J. Lathrop

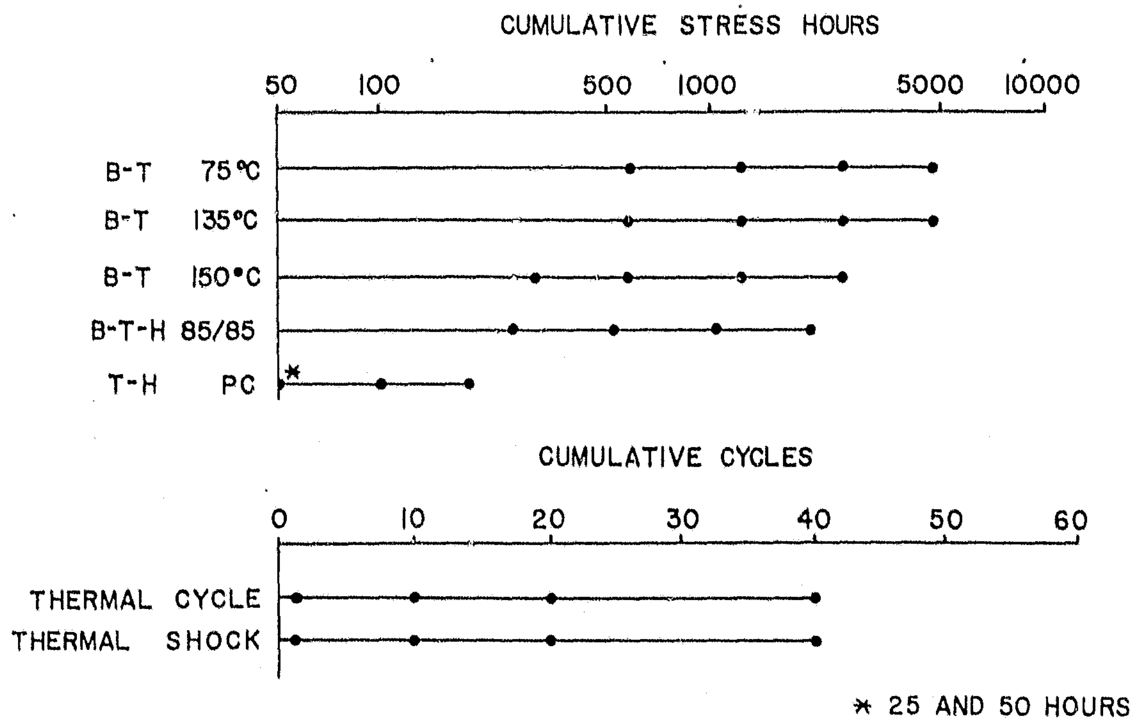
Solar Cell Metallization Systems Tested



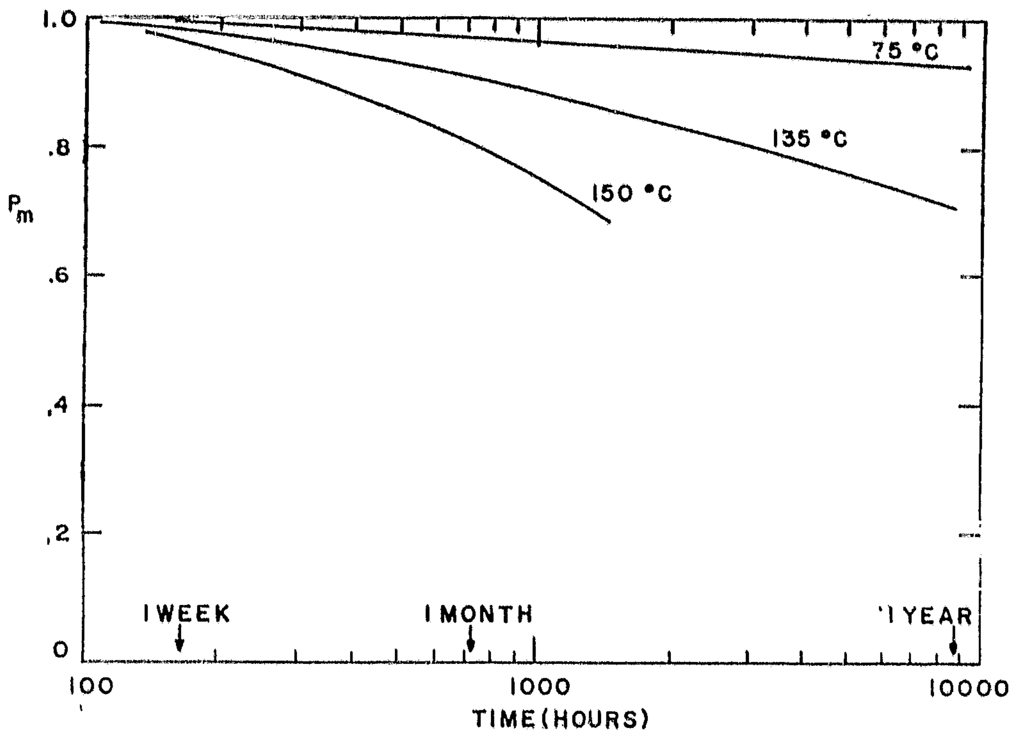
Relative Performance in Accelerated Stress Tests



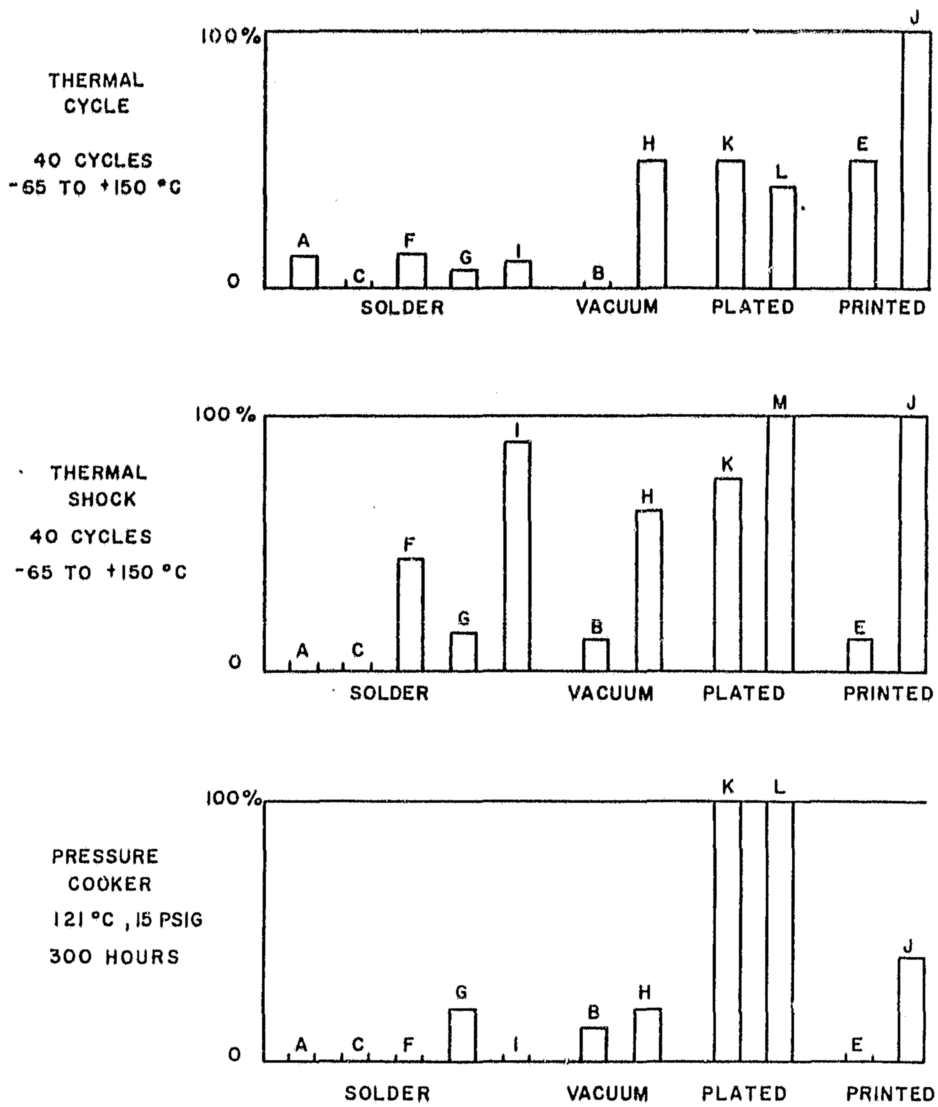
Accelerated Test Schedule



Average Normalized P_m as a Function of B-T Stress Time for A-Cells (Au-Ni-Solder)



Gross Failure Rates for Catastrophic Tests



Catastrophic Failure Mode Conclusions

Slice Fracturing

1) Brought on by thermal cycle/thermal shock
2) Little problem for vacuum cells
3) Moderate problem for other types

Open Lead (Metal-Silicon)

1) Only brought on by pressure cooker
2) Serious problem for plated cells

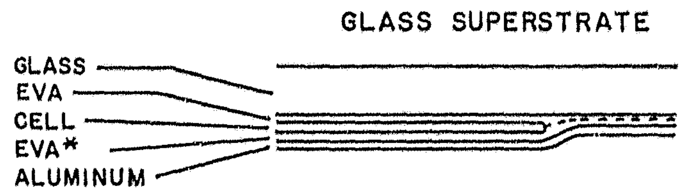
Open Lead (Metal-Metal)

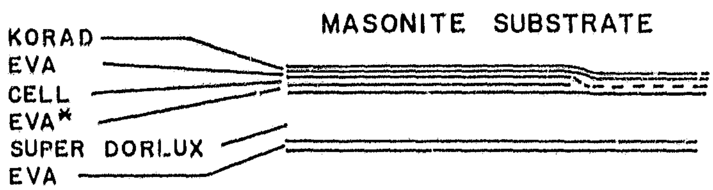
1) Mainly result of thermal cycle/thermal shock
2) Not a problem for solder or plated cells
3) Moderate problem for vacuum and printed cells

Open Lead (Silicon-Silicon)

1) Only brought on by thermal cycle/thermal shock
2) Not a problem for vacuum cells
3) Moderate problem for plated and printed cells
4) Can be workmanship/design problem for solder cells.

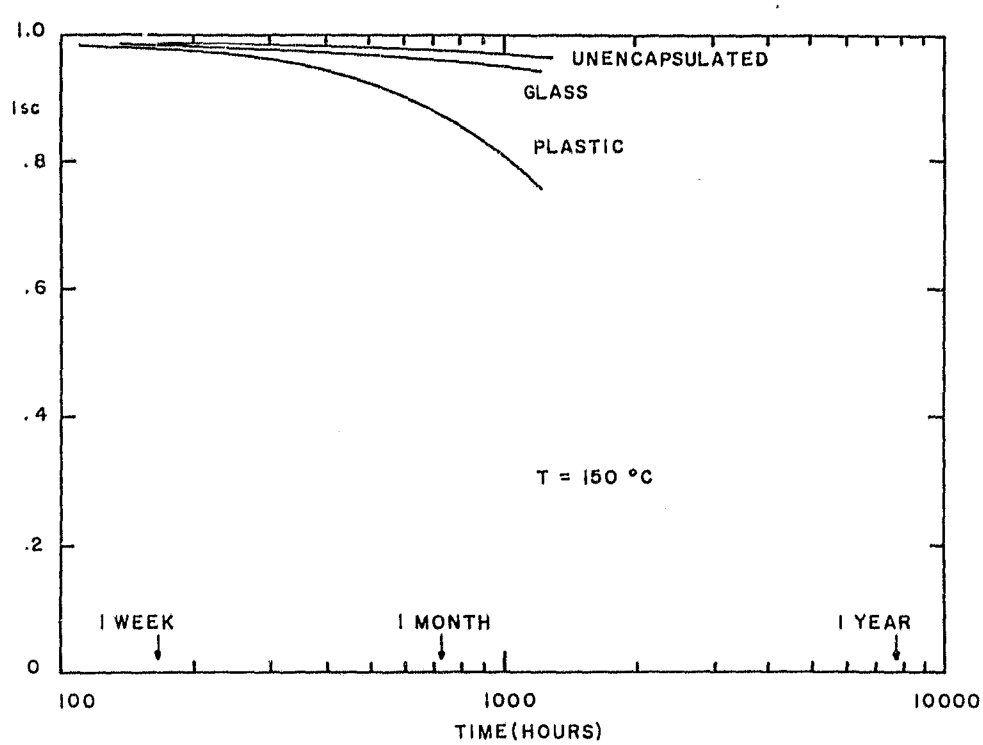
Minimodule Construction Detail



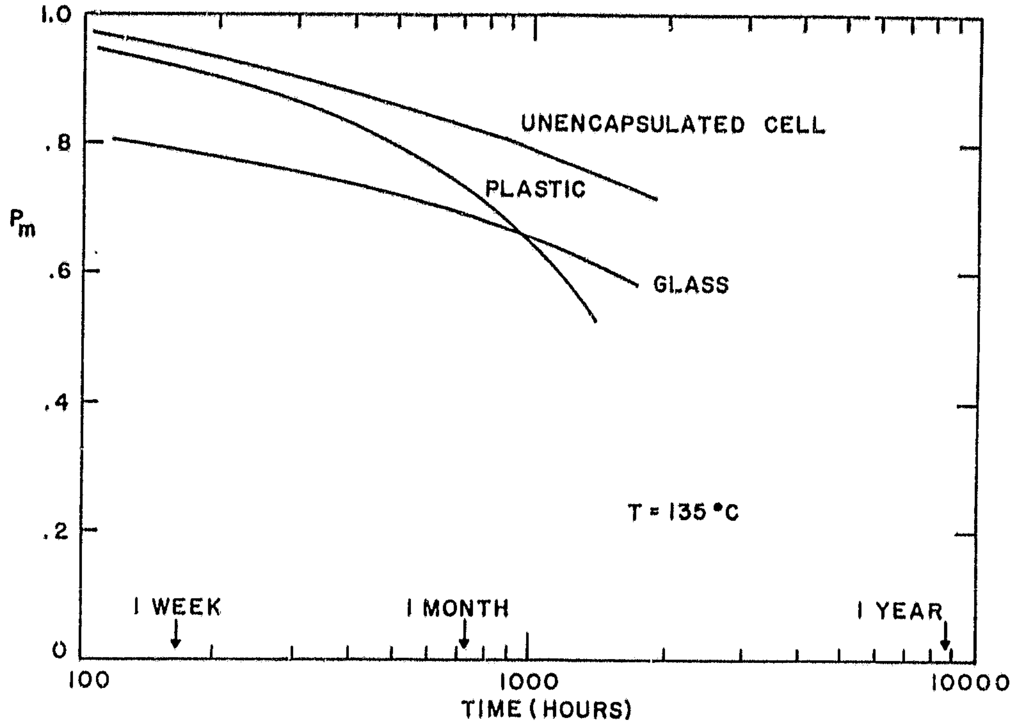


* EVA WITH GLASSMAT AND WHITE PIGMENT

Average Normalized I_{SC} as a Function of 150°C B-T Stress Time for Minimodules



Average Normalized P_m as a Function of 135°C B-T Stress Time for Minimodules



Encapsulated Cell Test Summary

HIGH TEMPERATURE (>120°C) TENDS TO INTRODUCE NEW FAILURE MODES ASSOCIATED WITH ENCAPSULATION AND IS NOT NECESSARILY AN ACCELERATING FACTOR.

NO INDICATION THAT ENCAPSULATION EITHER ENHANCES OR RETARDS ELECTRICAL DEGRADATION ASSOCIATED WITH TEMPERATURE (DIFFUSION) PHENOMENON.

NO INDICATION THAT ENCAPSULATION EITHER ENHANCES OR RETARDS ELECTRICAL DEGRADATION ASSOCIATED WITH PRESSURE COOKER (CORROSION) PHENOMENON.

SOME INDICATION THAT GLASS ENCAPSULATION MAY RESULT IN GREATER DEGRADATION DURING 85/85 TESTING.

PLASTIC ENCAPSULATION MAY BE SOMEWHAT MORE SENSITIVE TO THERMAL CYCLE STRESS THAN GLASS ENCAPSULATION.

COMPARISON OF U.S. AND FOREIGN ENVIRONMENTAL TESTING

JET PROPULSION LABORATORY

A.R. Hoffman

Sources

- U.S.

    JPL BLOCK PROCUREMENTS

    SERI INTERIM PERFORMANCE CRITERIA

    U.S. COAST GUARD

    DoD

- FOREIGN

    COMMISSION OF EUROPEAN COMMUNITIES (CEC, JRC)

    FRENCH (LCIE)

    AUSTRALIAN (TELECOM)

    JAPANESE (MANUFACTURER)

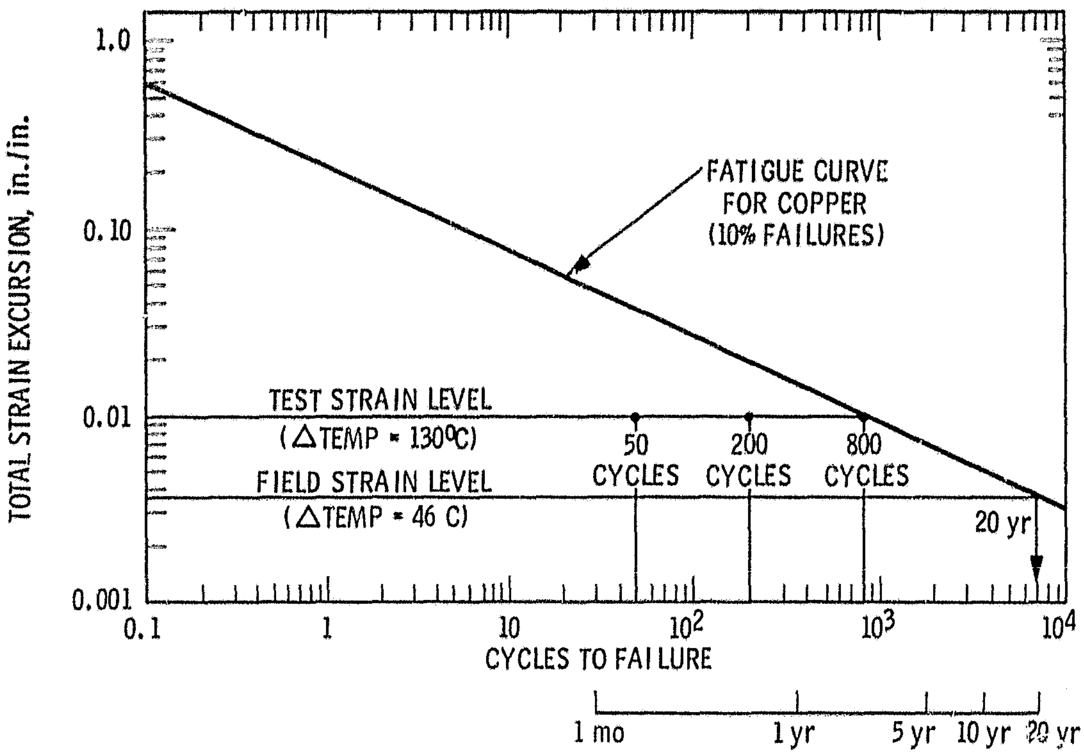
    CANADIAN (COAST GUARD)

Qualification Test Evolution

TESTS	MODULES					TEST LEVELS
	BLOCK I	BLOCK II	BLOCK III	BLOCK IV* RES/ILC	BLOCK V* RES/ILC	
THERMAL CYCLE	100	50	50	50	200	-40°C TO +90°C, CYCLES AS INDICATED
HUMIDITY CYCLE	X	5	5	5	10	5 CYCLES AT 95% RH, 23°C TO 40°C OR 10 CYCLES AT 85% RH, -40°C TO +85°C (BLK I, 70°C AT 90% RH, 68 H)
MECHANICAL LOADING CYCLE		100	100	10000	10000	2400 N/m^2 (50 lb/ft^2) CYCLES AS INDICATED
WIND RESISTANCE				X	X	UNDERWRITERS LAB TEST NO. 997 (RESIDENTIAL ONLY)
TWIST		X	X	X	X	ONE CORNER LIFTED 2 cm/m OF LENGTH
HAIL IMPACT				20	25	10 HITS WITH ICE BALLS, DIA AS INDICATED (mm)
ELECTRICAL ISOLATION		1500	1500	1500/2000	1500/3000	50 μA MAX CURRENT AT VOLTAGE INDICATED
HOT-SPOT ENDURANCE					X	100 h SHORT CIRCUITED AT 100 mW/cm^2, NOCT

*RES: RESIDENTIAL, ILC: INTERMEDIATE LOAD CENTER

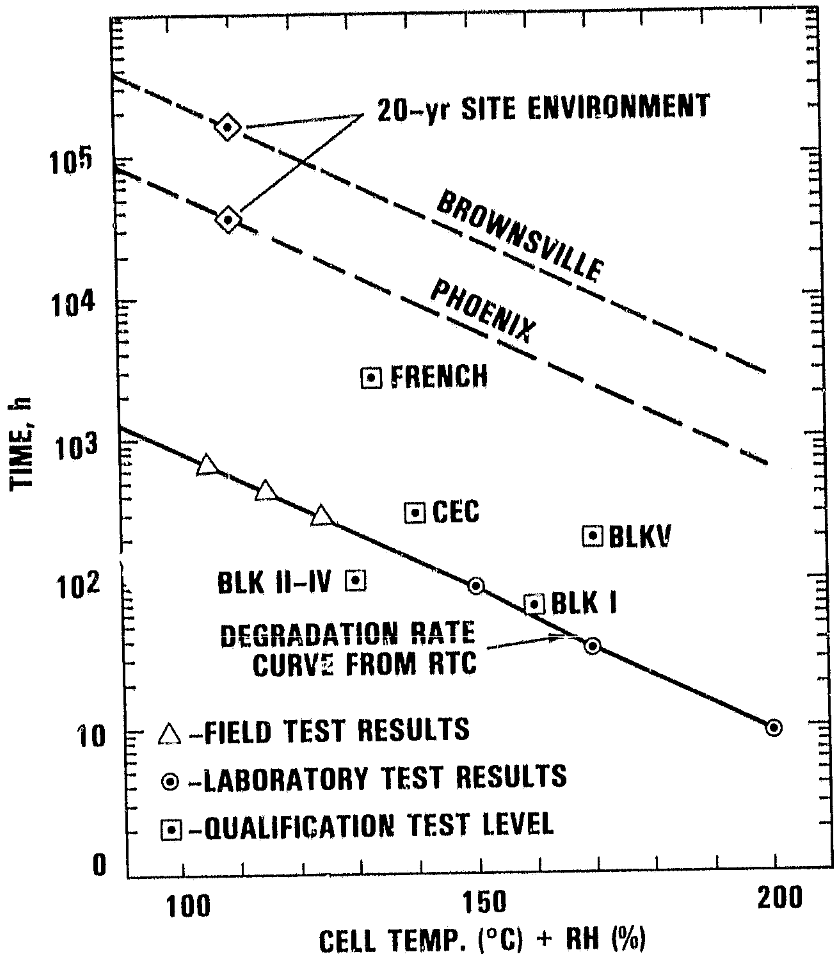
Thermal-Cycle Test Acceleration Factor (-40°C to +90°C)



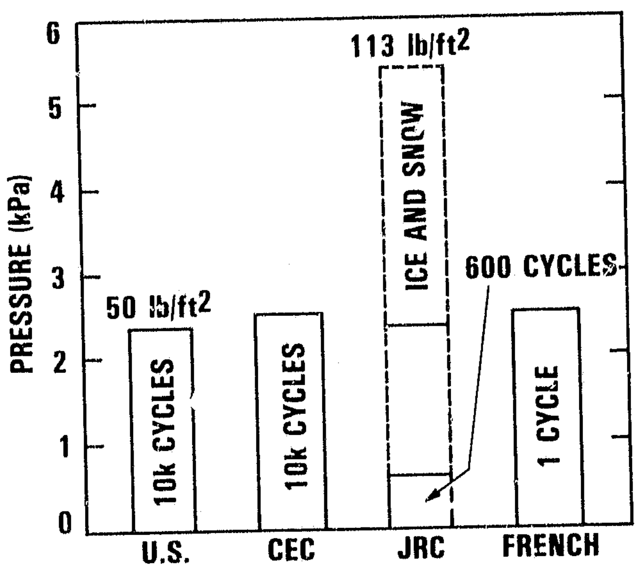
Time to Interconnect Field Failure

	TEST DESCRIPTION	TIME TO 10% INTERCONNECT FAILURE IN FIELD
U.S. (BLK II-IV)	-40°C TO +90°C, 50 CYCLES	1 yr 3 mo
U.S. (BLK V)	-40°C TO +90°C, 200 CYCLES	4 yr 10 mo
EUROPEAN 1 / FRENCH	-40°C TO +85°C, 200 CYCLES	4 yr 9 mo
EUROPEAN 2	-40°C TO NOCT +50°C, 50 CYCLES	1 yr 8 mo
JAPANESE	-40°C TO +80°C, 10 CYCLES	70 days

Acceleration of Humidity and Temperature



Loading Test Requirements



Mechanical Test Requirements

	U.S.	CEC*	JRC*	FRENCH*
TWIST	1.2°	1.2°	1.2°	–
HAIL IMPACT TERMINAL VELOCITY ICE BALL DIA (mm)	25	40	25	–
STEEL BALL IMPACT DIA (mm)/DROP HEIGHT (m)	51/1.3	–	–	40/1
WIND RESISTANCE (SHINGLES)	UL STD 997	–	–	–
ROBUSTNESS OF TERMINATIONS	89 N 20 lb/ft2	X	X	X
		BASED ON IEC 68-2-21		

*DRAFT

UV Test Requirements

- U.S. (SERI–IPC)
  - OUTDOOR
    - 9.56×10^8 J/m2 (REAL TIME)
    - 1.59×10^9 J/m2 (ACCELERATED)
  - CHAMBER
    - 9.56×10^8 J/m2
- CEC / JRC
  - 4.0×10^7 J/m2 (30 Mediterranean days)
  - (280 to 400 nm)
- FRENCH AND AUSTRALIAN
  - UNDER STUDY
- JAPANESE (MANUFACTURER)
  - 200 h CARBON-ARC ILLUMINATION
  - WITH PERIODIC WATER SPRAY

Electrically Induced Test Requirements

	U.S.	CEC	JRC	FRENCH	JAPANESE
HIGH POTENTIAL TEST	50 μA MAX CURRENT 1500V/3000V	–	50 μA CURRENT 2V+1000	–	–
HOT-SPOT ENDURANCE	100 h SHORT-CIRCUITED AT NOCT AND 1000 mW/cm^2	–	50 h SHORT-CIRCUITED AT NOCT AND I_{AV} at V_R	– –	– –
INSULATION RESISTANCE	1500V/3000V, 1 min >30 mΩ, >60 mΩ	$\pm$1000V, 1 min >100 mΩ	$\pm$1000V, 1 min >100 mΩ	–	500V >500 mΩ

Salt Fog Test Requirements

- **EUROPEAN TESTS BASED ON IEC 68-2-11**
  35°C, 5% NaCl, 96 h

- **JAPANESE TEST: SALT-WATER SPRAY**
  5% NaCl, 100 h

Special Application Test Requirements

- U. S. COAST GUARD
  PRESSURE, IMMERSION, TEMPERATURE (PIT TEST)
  5 lb/IN.^{2}(g); 50^{0}C AND 5^{0}C SALT WATER
  2000 CYCLES

- CANADIAN COAST GUARD
  SALT WATER TESTS

Candidate Test Requirements

ICE FORMATION (JRC)

ABRASION (FRENCH)

EASE OF CLEANING (FRENCH)

OZONE (JRC)

SO_2 (JRC)

INDUSTRIAL POLLUTION (FRENCH)

Conclusions

- **FOREIGN REQUIREMENTS BASED ON JPL SPECS, INFLUENCED BY OWN EXPERIENCE AND IEC REQUIREMENTS**
- **SIMILAR FOR MOST MECHANICAL AND ELECTRICAL-STRESS TESTS**
- **RESEARCH ADDRESSING DIFFERENCES IN HUMIDITY-FREEZE, TEMPERATURE SOAK, HUMIDITY-SOAK, AND UV**

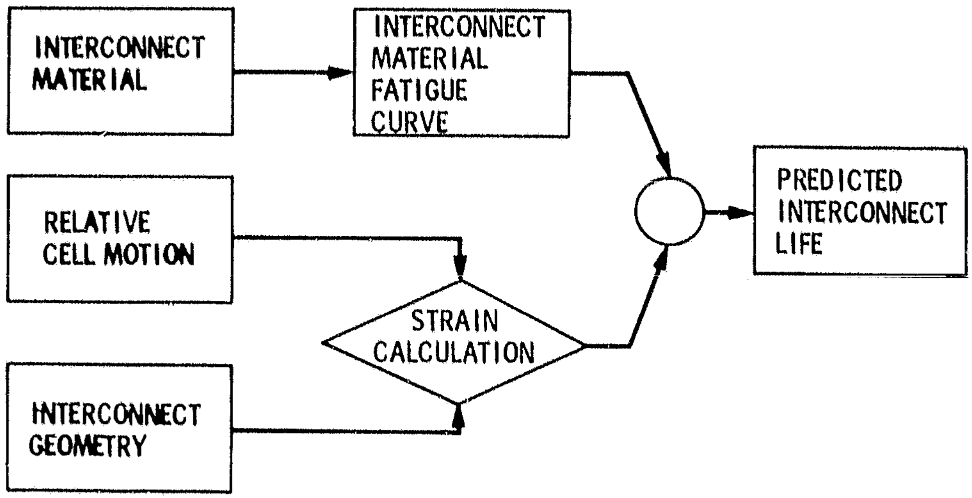
CALCULATION OF STRAIN IN CELL INTERCONNECTS

JET PROPULSION LABORATORY

D.M. Moore

Objective

- DEVELOP A SIMPLE TECHNIQUE FOR CALCULATING STRAIN IN INTERCONNECT MATERIAL FOR PREDICTION OF INTERCONNECT FATIGUE LIFE



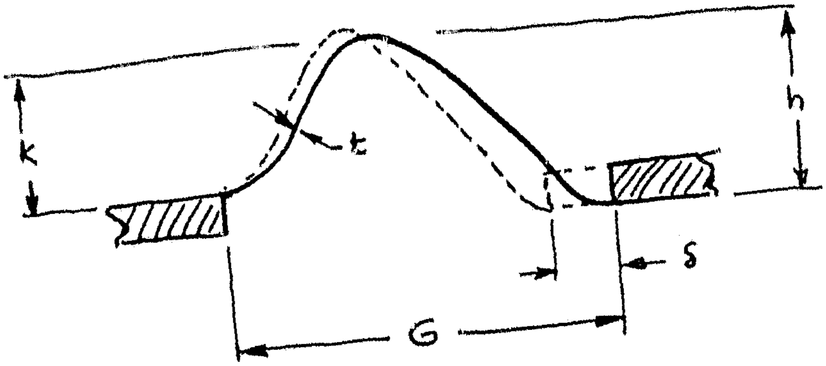
Approach

- DEVELOP FINITE-ELEMENT AND CLOSED FORM ANALYTICAL MODELS TO PREDICT THE MAXIMUM LOCAL STRAIN IN THE INTERCONNECT MATERIAL

- IDENTIFY THE DOMINANT GEOMETRIC PARAMETERS

- CONSTRUCT A NOMOGRAPH PERMITTING RAPID CALCULATION OF INTERCONNECT STRAIN AS A FUNCTION OF THESE DIMENSIONLESS PARAMETERS

Interconnect Strain

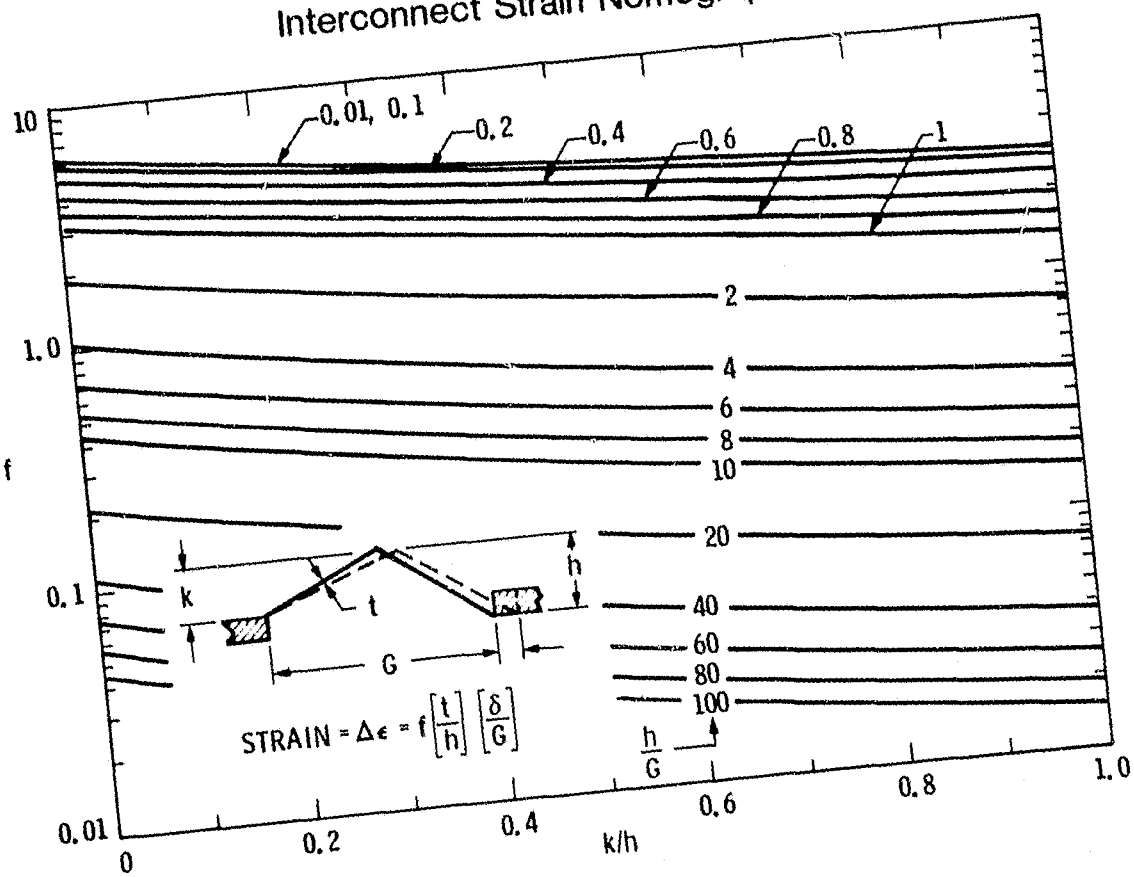


$\Delta\epsilon$ = PEAK TO PEAK STRAIN EXCURSION

$$= f\left(\frac{t}{h}\right)\left(\frac{\delta}{G}\right)$$

WHERE f = FUNCTION OF $\frac{h}{G}$ AND $\frac{k}{h}$

Interconnect Strain Nomograph



Example: Interconnect Fatigue Failure Prediction

PARTICULARS

- BLOCK II MODULE
- RANDOM ORIENTED FIBERGLASS SUBSTRATE
- 192 MODULES INSTALLED NOVEMBER 1978
- 34 MODULES FAILED AS OF MAY 1980 DUE TO BROKEN INTERCONNECTS

Cell Interconnect Deflection

- TOTAL TEMPERATURE EXCURSION

ΔT_{DN} = 14^0C (YEARLY AVERAGE)
ΔT_{OP} = 32^0C (AT 100 mW/cm^2)

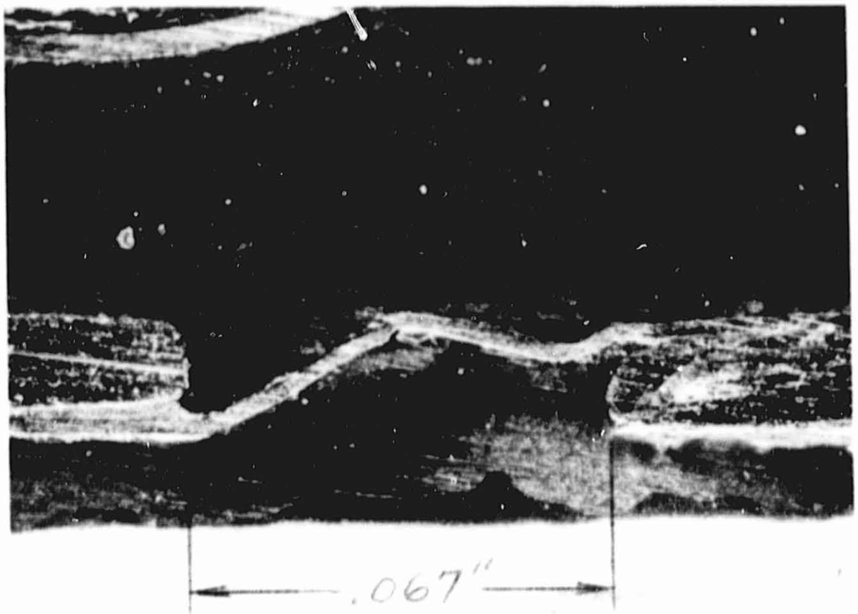
ΔT = 46^0C (YEARLY AVERAGE)

- THERMAL EXPANSION COEFFICIENTS

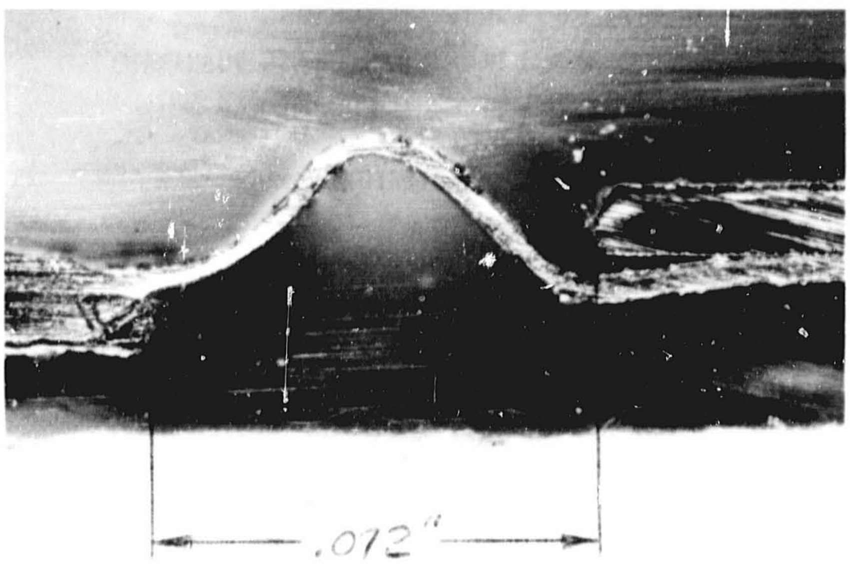
α_S = $2.78 \times 10^{-5}/^0C$ (FIBERGLASS SUBSTRATE)
α_C = $.29 \times 10^{-5}/^0C$ (SILICON SOLAR CELL)

- CELL INTERCONNECT DEFLECTION

$$\delta = (\alpha_S C - \alpha_C D)\,\Delta T$$
$$= .0035''$$



Cell Interconnect B2, Sectioned from Solarex Block II
Module S/N 023134



Cell Interconnect G2, Sectioned from Solarex Block II
Module S/N 0234134

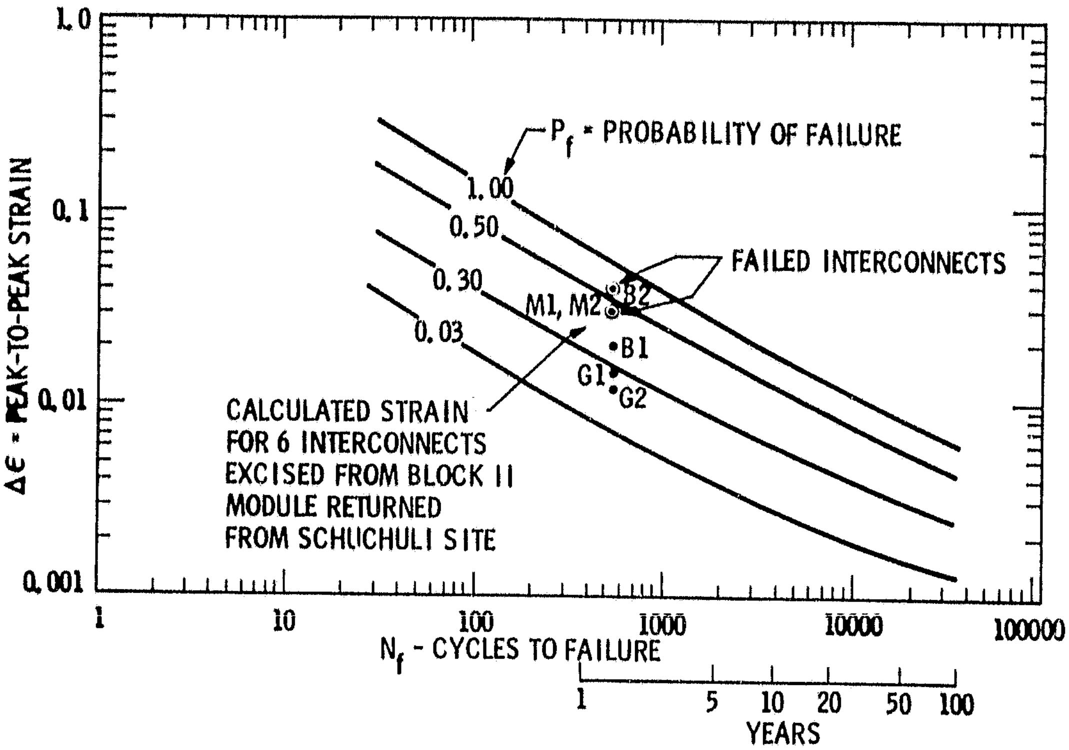
Calculate Interconnect Strain

$$\Delta\epsilon = f\left(\frac{t}{h}\right)\left(\frac{\delta}{G}\right)$$

FROM NOMOGRAPH

NO.	CONFIGURATION	h/G	k/h	f	$\Delta\epsilon$
B1	k = 0.007, h = 0.024, G = 0.077	0.31	0.292	4.15	0.0196
B2	k = 0.0019, h = 0.0167, G = 0.073	0.23	0.114	5.20	0.0373
G1	h = 0.0244, k = 0.0148, G = 0.069	0.35	0.607	3.15	0.0164
G2	k = 0.0219, h = 0.0235, G = 0.072	0.33	0.932	2.63	0.0136
M1	k = 0.0071, h = 0.0175, G = 0.072	0.24	0.406	3.90	0.0270
M2	h = 0.0159, k = 0.0069, G = 0.076	0.21	0.434	3.95	0.0286

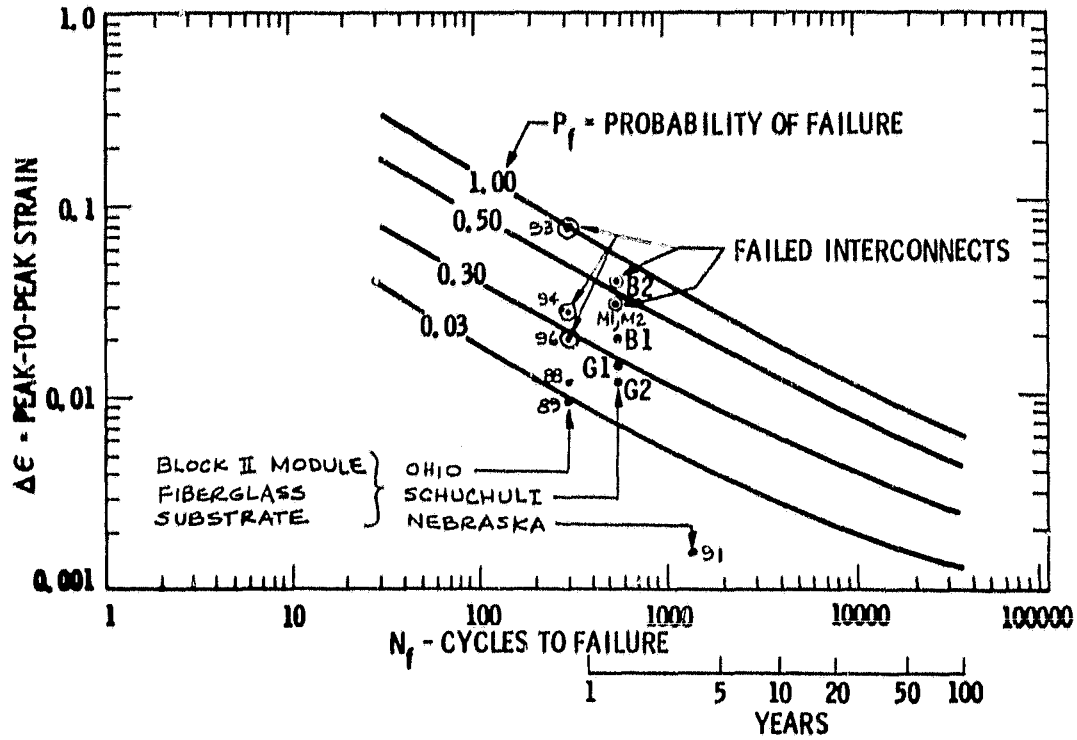
Interconnect Fatigue Curve: Annealed OFHC Copper



Failed Model D Modules With Broken Interconnects

SITE (MFG)	TOTAL NO. OF MODULES	TOTAL NO. OF FAILURES	FAILURES WITH BROKEN INTER-CONNECTS	TIME
NEB (D-II)	728	39	5	3 2/3 YRS.
OHIO (D-III)	800	46	44	5/6 YR.
RES STF (D-III)	192	13	13	2 1/2 YRS.
ROOF STF (D-III)	74	2	2	2 1/2 YRS.

Interconnect Fatigue Curve: Annealed OFHC Copper



HOT-SPOT HEATING STUDIES

JET PROPULSION LABORATORY

S.D. Glazer

Objectives

- DEVELOP GUIDELINES FOR FUTURE DESIGNS
- DEVELOP ANALYTICAL MODEL TO PREDICT HOT-SPOT TEMPERATURES
- DEVELOP SIMPLE DESIGN TOOL

Cases Run

A. UNINSULATED MODULE, LIGHT + POWER

B. INSULATED BACK MODULE, LIGHT + POWER

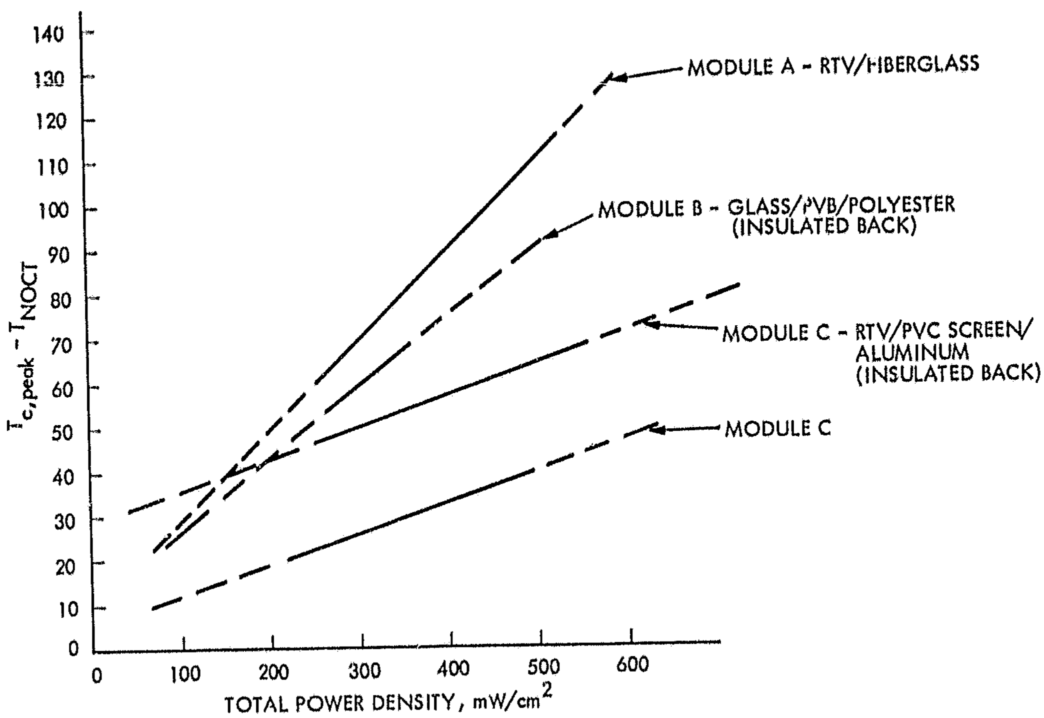
C. UNINSULATED MODULE, LIGHT, NO POWER

D. UNINSULATED MODULE, POWER, NO LIGHT

(A–D: INDOOR LAB TESTS)

E. OUTDOOR TEST IN NATURAL SUNLIGHT, WITH POWER

Selected Hot-Spot Test Results: Peak ΔT vs Total Power Density for Several Modules

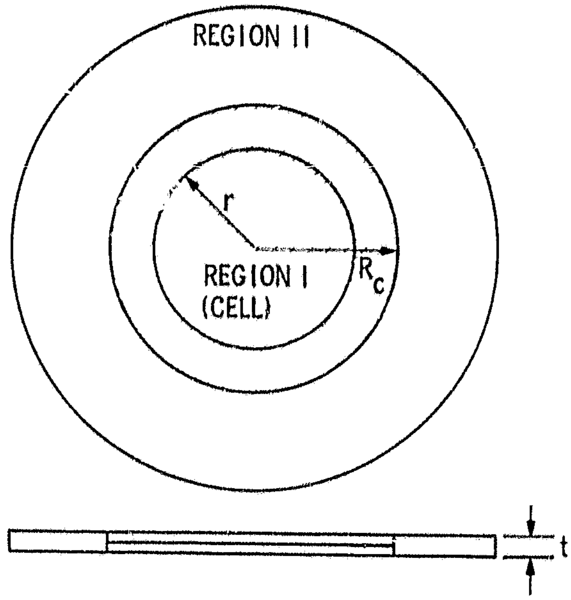


Analytical Thermal Model

KEY FEATURES
- 1-D MODEL GEOMETRY
- CONVECTION + LINEARIZED RADIATION HEAT TRANSFER
- HANDLES INSULATED AND UNINSULATED MODULE BACK
- SIMPLE CLOSED-FORM SOLUTION

REQUIRES
- MODULE + CELL GEOMETRY
- k, ρ OF MATERIALS
- AMBIENT CONDITIONS
- SOLAR FLUX + BACK-BIAS POWER

YIELDS
- TEMPERATURE PROFILE + PEAK CELL TEMPERATURE
- SENSITIVITY ANALYSIS



STEADY-STATE ENERGY BALANCE: REGION I

$$\underbrace{\frac{1}{r}\frac{d}{dr}\left(k_1 \, tr \frac{dT}{dr}\right)}_{\text{HEAT CONDUCTED THROUGH MODULE}} + \underbrace{\left[\alpha_1 q_s'' + P_{BB}\right]}_{\text{INSOLATION + BACK-BIAS ENERGY}} \underbrace{- 2h_{eff}(T - T_a)}_{\text{CONVECTIVE + RADIATIVE HEAT LOSS}} = 0$$

REGION II

$$\frac{1}{r}\frac{d}{dr}\left(k_2 \, tr \frac{dT}{dr}\right) + \alpha_2 q_s'' - 2h_{eff}(T - T_a) = 0$$

SOLUTION FORM

$$T_{HOT\ SPOT} - T_a = \Delta T_{PEAK} = \frac{\alpha_1 q_s''}{2h_{eff}} + \frac{P_{BB}}{2h_{eff}}\left[1 - \frac{K_1(m_2R_c)}{\left(\frac{k_1}{k_2}\right)^{1/2} K_0(m_2R_c)\, I_1(m_1R_c) + K_1(m_2R_c)\, I_0(m_1R_c)}\right]$$

Predicted ΔT_{peak} Sensitivities to Selected Parameters

NOMINAL MODULE GEOMETRY: GLASS/PVB/POLYESTER

NOMINAL $\Delta T_{peak} = T_{HOT\ SPOT} - T_{NORMAL\ CELL} = 32.2°C$

PARAMETER	NOMINAL	NEW	% PARAMETER CHANGE	ΔT_{peak}, NEW	% ΔT_{peak} CHANGE
CELL THICKNESS, in.	0.015	0.0075 0.030	-50 +100	83.4 23.6	+159 -27
CELL DIAMETER, in.	2.0	4.0	+100	60.7	+89
SUBSTRATE	0.005 POLYESTER FILM	0.005 ALUM.		16.6	-48
REAR SURFACE EMITTANCE	0.91	0.04	-96	38.0	+18
INSULATED BACKSIDE	NO	YES		44.1	+37
BACK-BIAS POWER FLUX, mW/cm^2	271	542	+100	64.4	+100

NOTE: $\% \Delta T_{peak}$ CHANGE $\dfrac{\Delta T_{peak,\ NEW} - \Delta T_{peak,\ NOMINAL}}{\Delta T_{NOMINAL}}$

Model Predictions vs Experimental Data

MODULE	INSULATED BACK?	INSOLATION FLUX, mW/cm^2	BACK-BIAS POWER, W	T_{meas} °C	T_{pred} °C
A = GLASS/PVB/POLYESTER	N	87.1	3.72	70.0	73.4
A = GLASS/PVB/POLYESTER	N	0	6.8	89.1	82.9
A = GLASS/PVB/POLYESTER	Y	0	7.4	111.2	114.5
A = GLASS/PVB/POLYESTER	Y	0	1.84	70.5	69.0
B = GLASS/PVB/TEDLAR	N	77.5	15.0	125.0	126.6
C = RTV/POLYESTER	N	79.4	14.56	121.0	116.8
D* = RTV/ALUMINUM	N	89.0	3.84	68.25	45.42

*FINNED ALUMINUM SUBSTRATE

RESIDENTIAL ARRAY DEVELOPMENT

GENERAL ELECTRIC CO.

N.F. Shepard

Program Objectives

- DEFINE AN INTEGRATED RESIDENTIAL MODULE/ARRAY DESIGN WHICH MEETS THE 1982 TECHNOLOGY READINESS GOALS
  - SUPPLY DETAILED DRAWINGS AND MATERIAL SPECIFICATIONS COMPATIBLE WITH LOW-COST, MASS PRODUCTION PROCESSES CURRENTLY IN USE
  - PROVIDE INSTALLATION DETAILS AND INSTRUCTIONS
- ASSEMBLE A PROTOTYPICAL ARRAY SECTION TO DEMONSTRATE THE SELECTED CONCEPT

Current Status

- DETAILED DESIGN OF SELECTED MODULE -- COMPLETE
- INSTALLATION DETAILS -- COMPLETE
- PRODUCTION COSTING ANALYSIS -- COMPLETE FOR 50,000 M^2 PER YEAR
  -- OTHER RATES TO BE INCLUDED IN QUARTERLY REPORT NO. 3
- INSTALLATION COST ESTIMATES -- COMPLETE (PRELIMINARY)
  -- TO BE REFINED FOR INCLUSION IN QUARTERLY REPORT NO. 3
- PROTOTYPE ARRAY ROOF SECTION -- CONCEPTUAL DESIGN COMPLETE

Program Assumptions and Constraints

- DEVELOPMENT OF CELLS AND ENCAPSULATION SYSTEMS NOT WITHIN WORK SCOPE
- BLOCK V RESIDENTIAL DESIGN, CONSTRUCTION AND TESTING REQUIREMENTS
- ARRAY SIZE APPROXIMATELY 74 M^2 PER HOUSE
- ARRAY DESIGN SHOULD PERMIT EXPANSION FOR VARIOUS SIZE HOUSES BETWEEN 140 AND 280 M^2 OF FLOOR SPACE
- CELL COST DATA SUPPLIED BY JPL
- USE 6 PERCENT DISCOUNT RATE FOR LIFE-CYCLE COST ESTIMATES
- COSTS TO BE IDENTIFIED IN 1980 DOLLARS
- ENCAPSULATED CELL EFFICIENCY OF 13.5 PERCENT AT 100 mW/cm^2 AND 28°C
- A CELL OPEN-CIRCUIT FAILURE RATE OF ONE CELL PER TEN THOUSAND PER YEAR

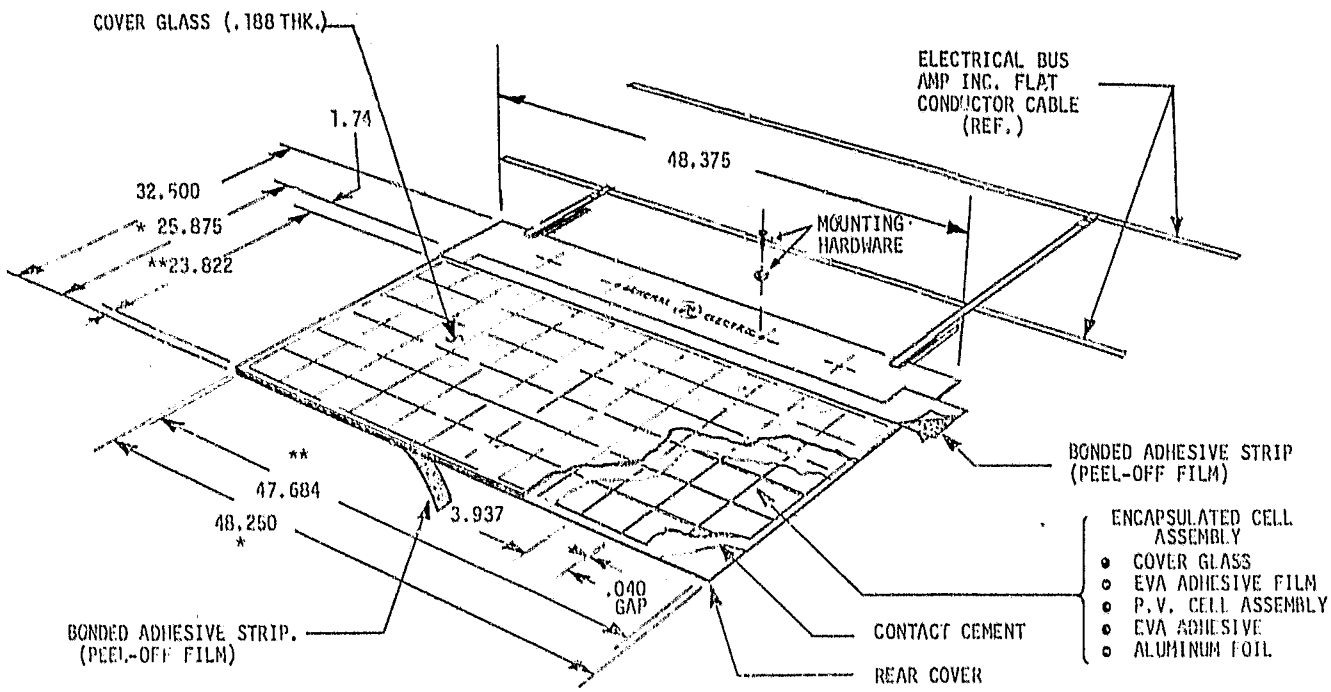
Annual Production Rates for Costing Analysis

ANNUAL PRODUCTION RATE (M^2/YEAR)	10,000	50,000	500,000
NUMBER OF SOLAR CELLS	1,000,000	5,000,000	50,000,000
NUMBER OF MODULES	13,889	69,444	694,444
POWER OUTPUT AT PEAK POWER RATING CONDITIONS (MW)	1.35	6.75	67.5

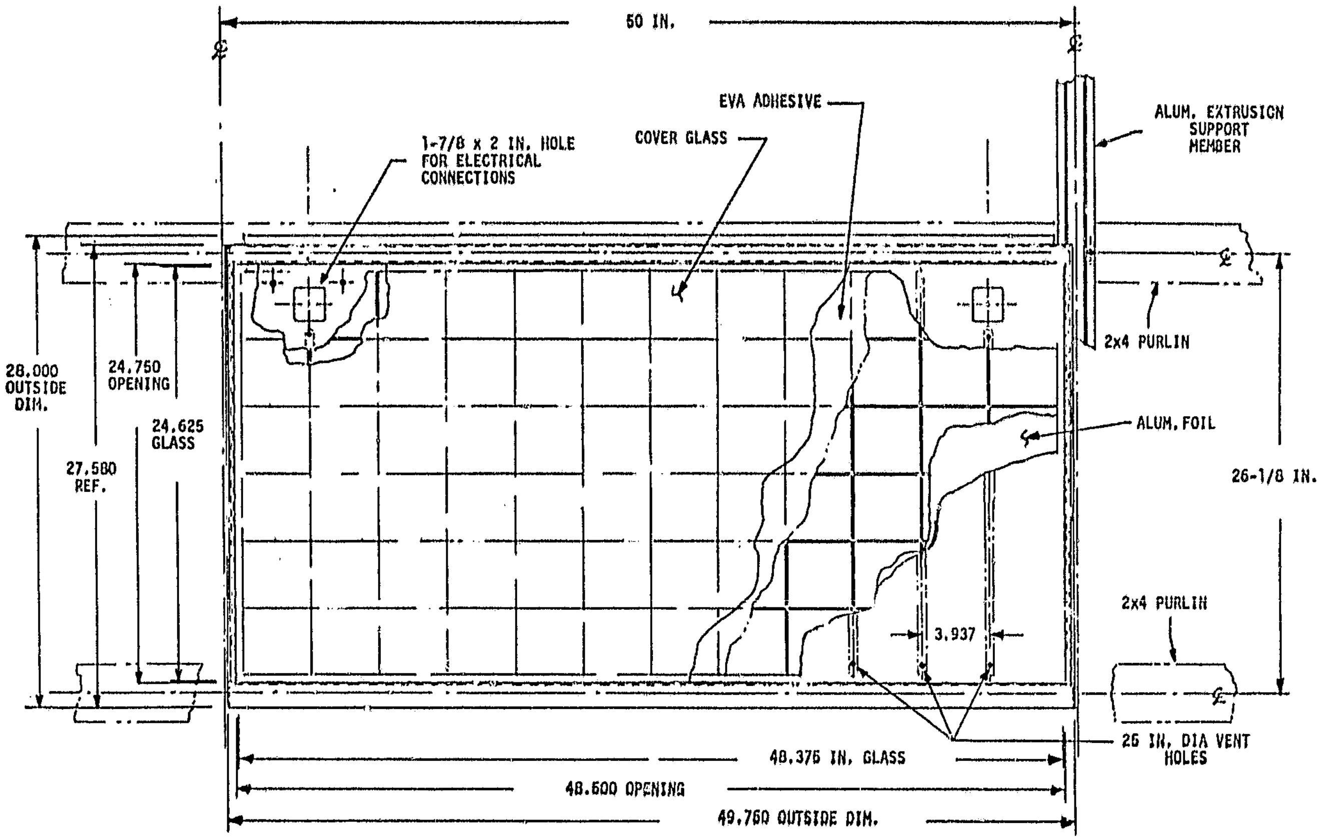
Observations From Previous Experience

- METAL SUBSTRATES LEAD TO RELIABILITY AND SAFETY PROBLEMS.
- POLYMERIC OUTER COVERS HAVE QUESTIONABLE LONG-TERM WEATHER-ABILITY AND FIRE-RESISTANCE.
- EXPOSED CONDUCTIVE ELEMENTS REQUIRE GROUNDING WITH ASSOCIATED COST.
- HIGH AREAL POWER DENSITY IS REQUIRED FOR MINIMUM INSTALLED COST.
- SAFETY IS A CRITICAL DESIGN CONCERN.

Concept No. 1: Direct-Mounted, Overlapping Shingle



Concept No. 2: Integrally Mounted With Plastic Tray



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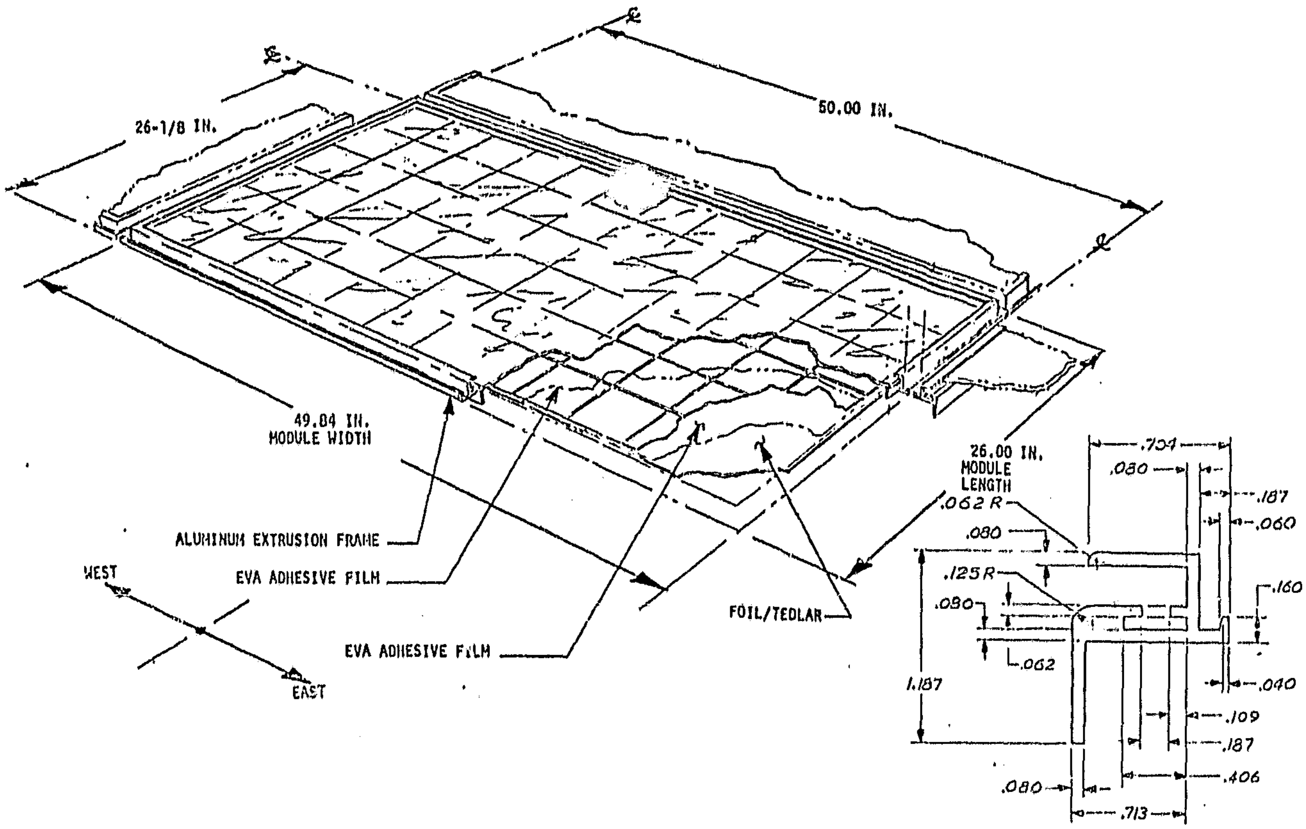
Concept No. 3: Stand-off Mounted With Aluminum Frame



Cost Comparison (1980 \$/Module)

	DIRECT-MOUNTED OVERLAPPING SHINGLE	INTEGRALLY-MOUNTED WITH PLASTIC TRAY	STAND-OFF MOUNTED ALUMINUM FRAME
PRODUCTION COST (EXCLUSIVE OF SOLAR CELLS)	88.36	86.02	83.27
INSTALLATION COST	39.91	33.26	39.75
TOTAL:	128.27	119.28	123.02

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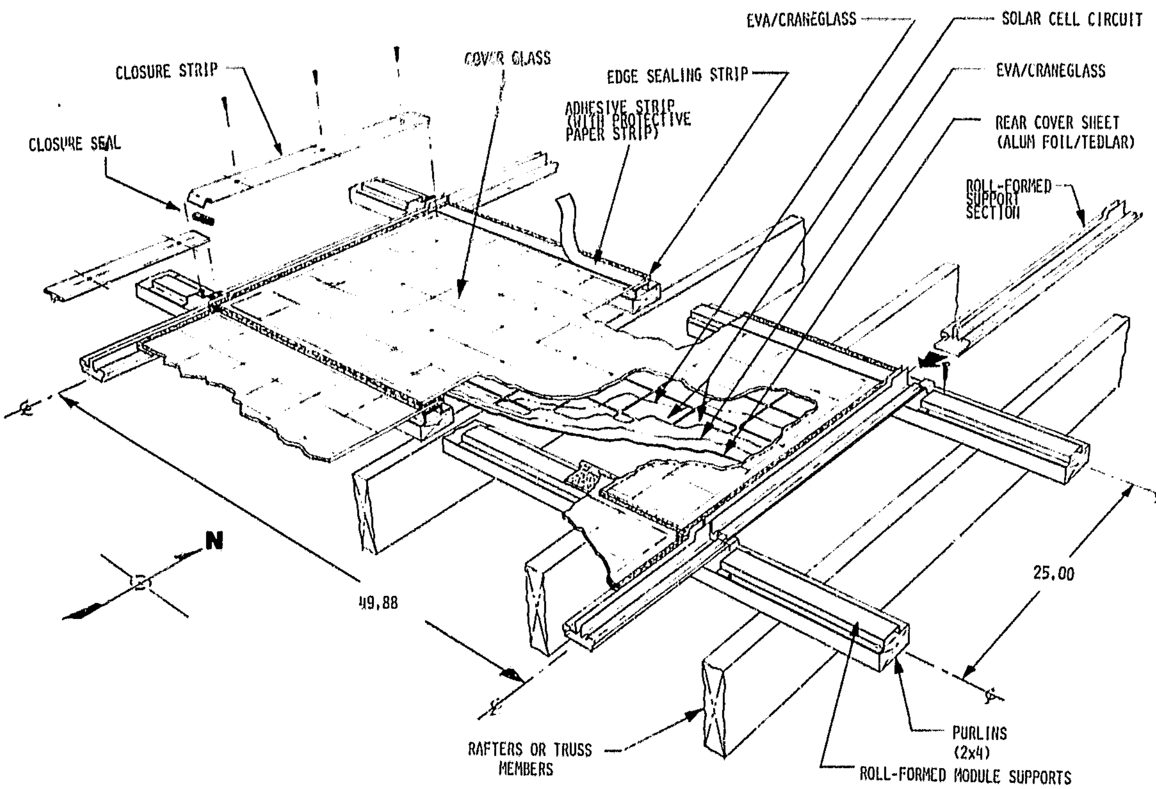
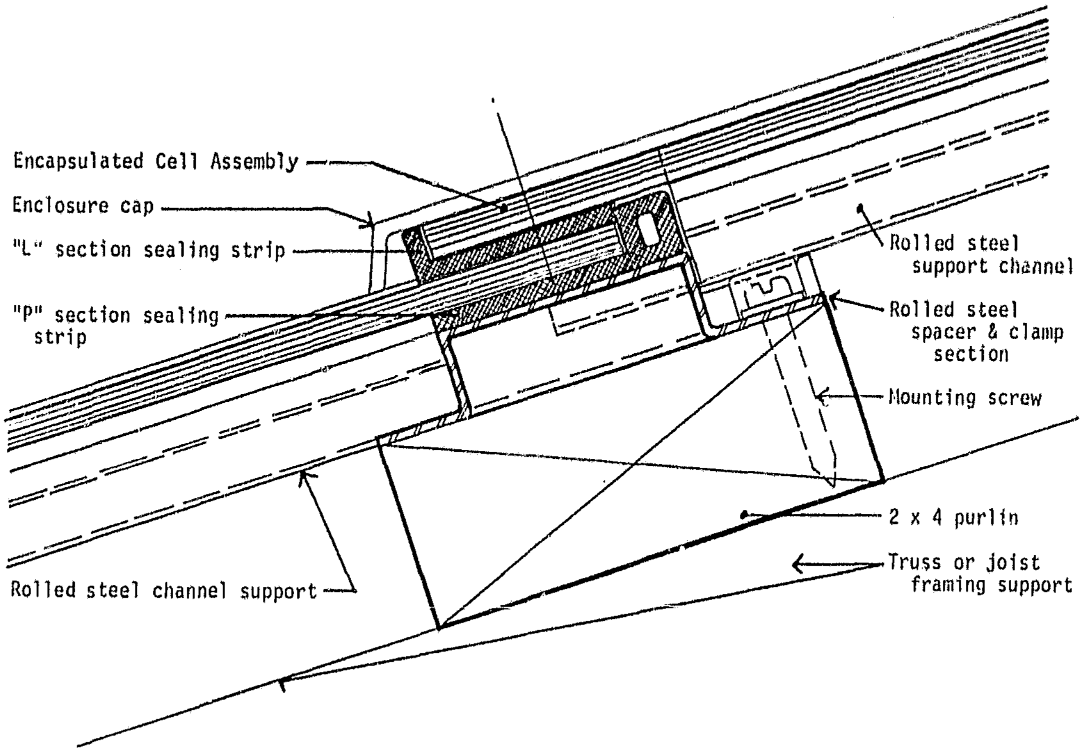
Desirable Features of an Optimized Module/Array

- FURTHER REDUCTION IN MODULE PRODUCTION COST THROUGH DESIGN SIMPLIFICATION AND REDUCED MATERIAL CONTENT.
- RETAIN LOW INSTALLATION COST ASSOCIATED WITH THE INTEGRAL MOUNTING SCHEME.
- INCORPORATE DESIGN FEATURES TO PERMIT UNIVERSAL MOUNTING (DIRECT, INTEGRAL, OR STAND-OFF).

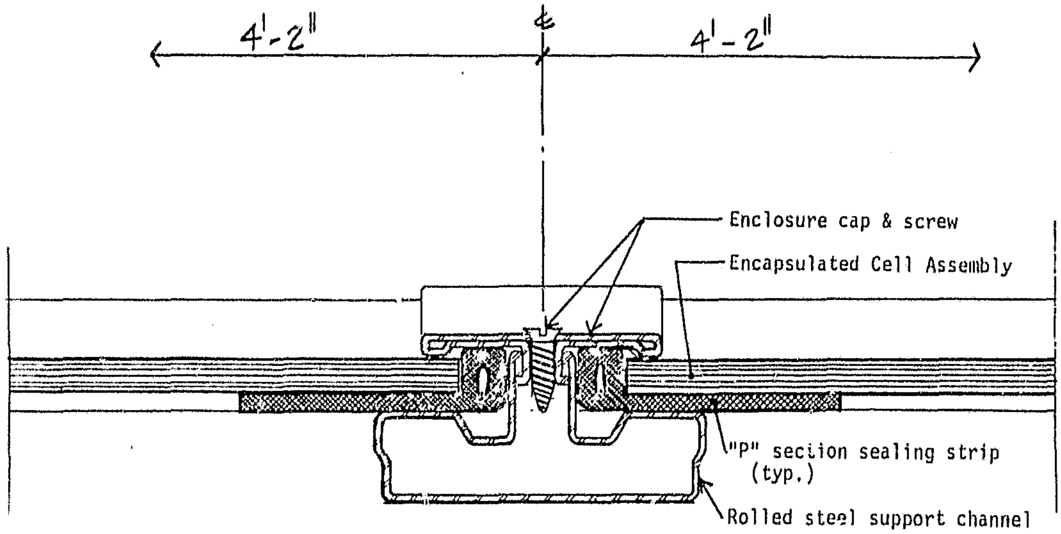
Selected Array/Module Design



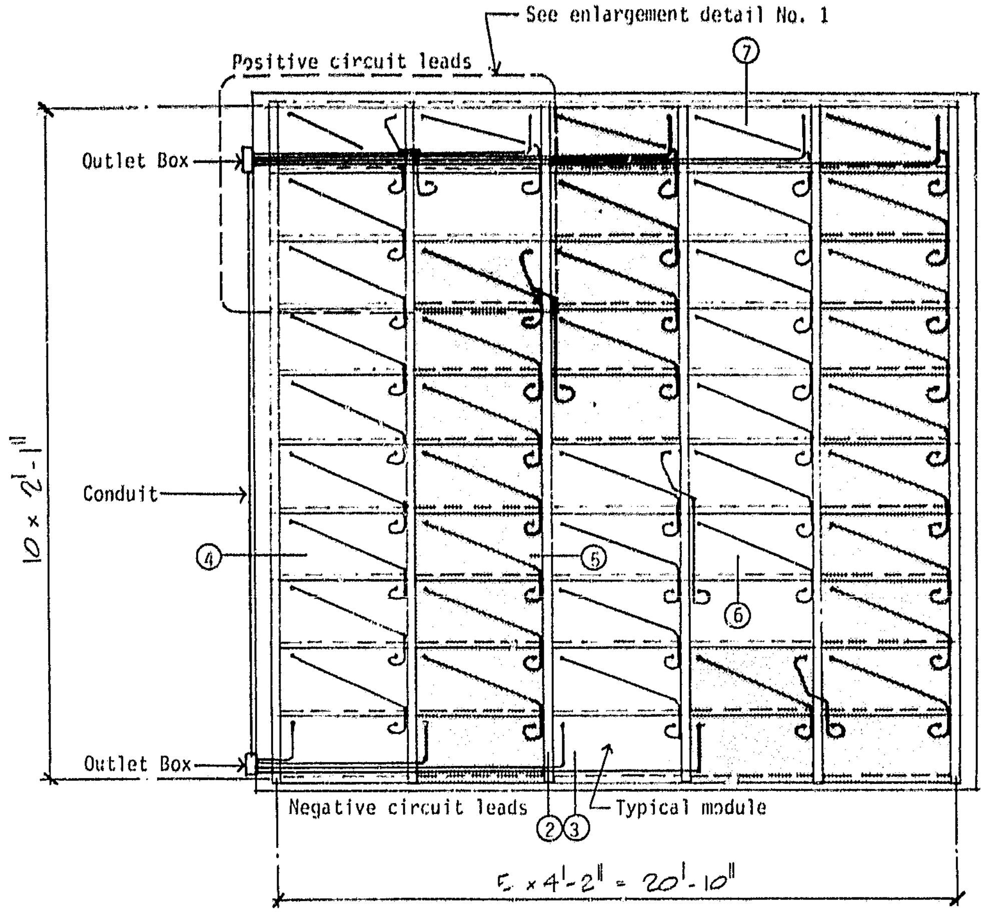
Section Through Horizontal Overlap



Section Through N-S Channel



Array Layout and Wire Routing



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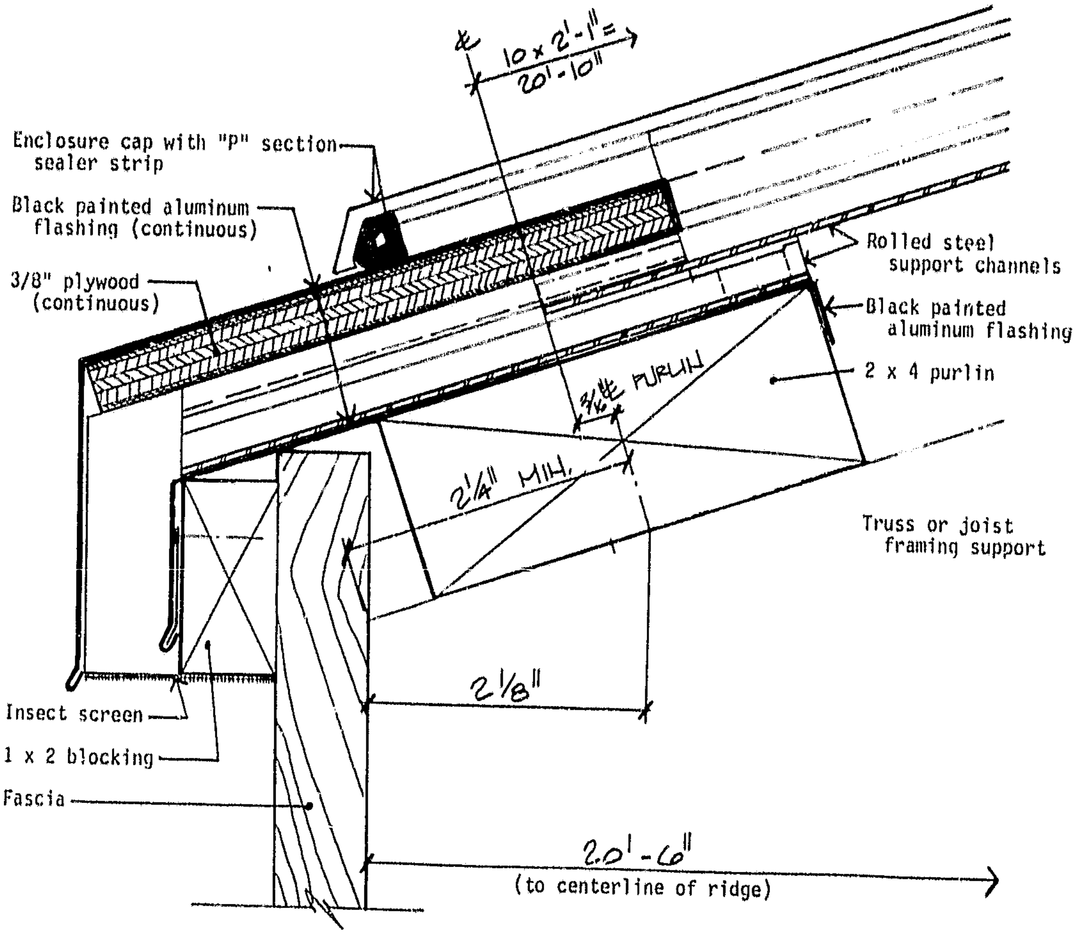
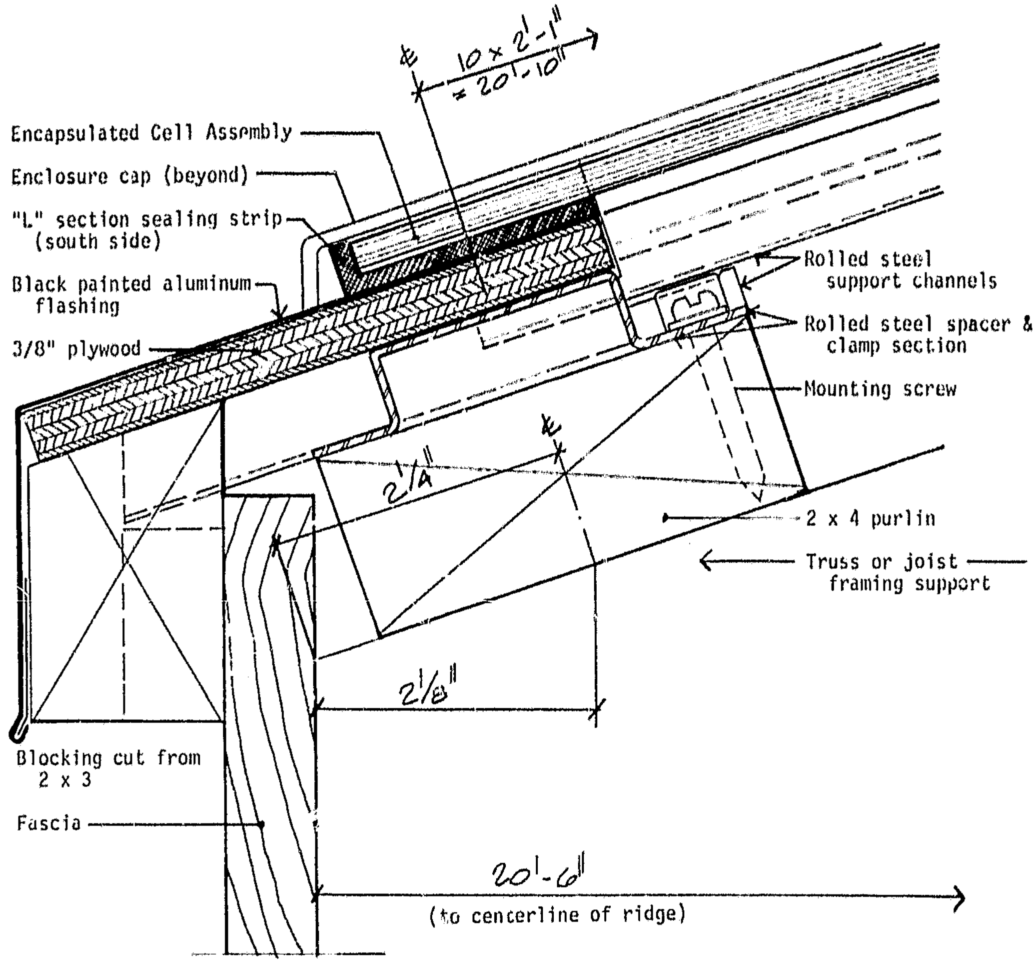
Integral Mount: Eave Detail at Channel



Integral Mount: Eave Detail Between Channels



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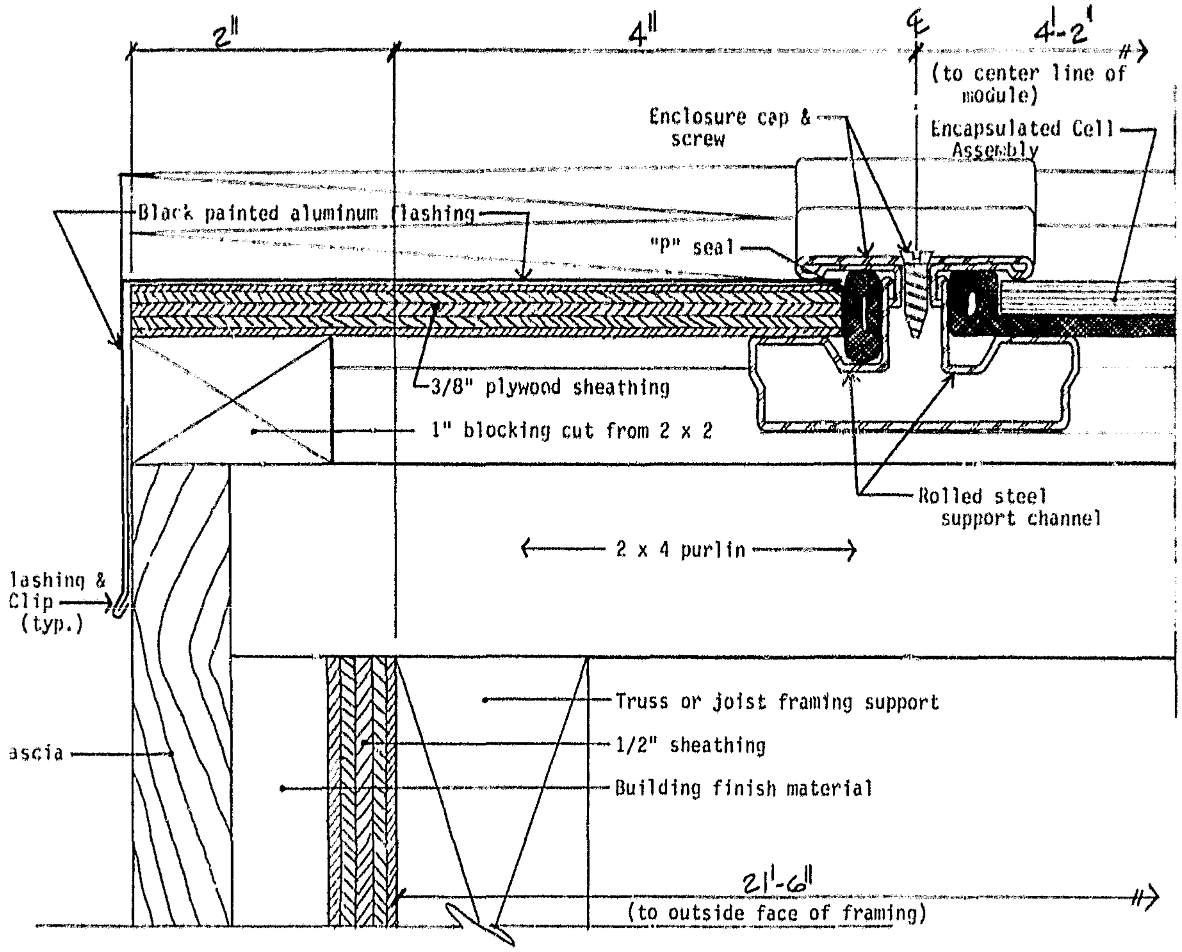
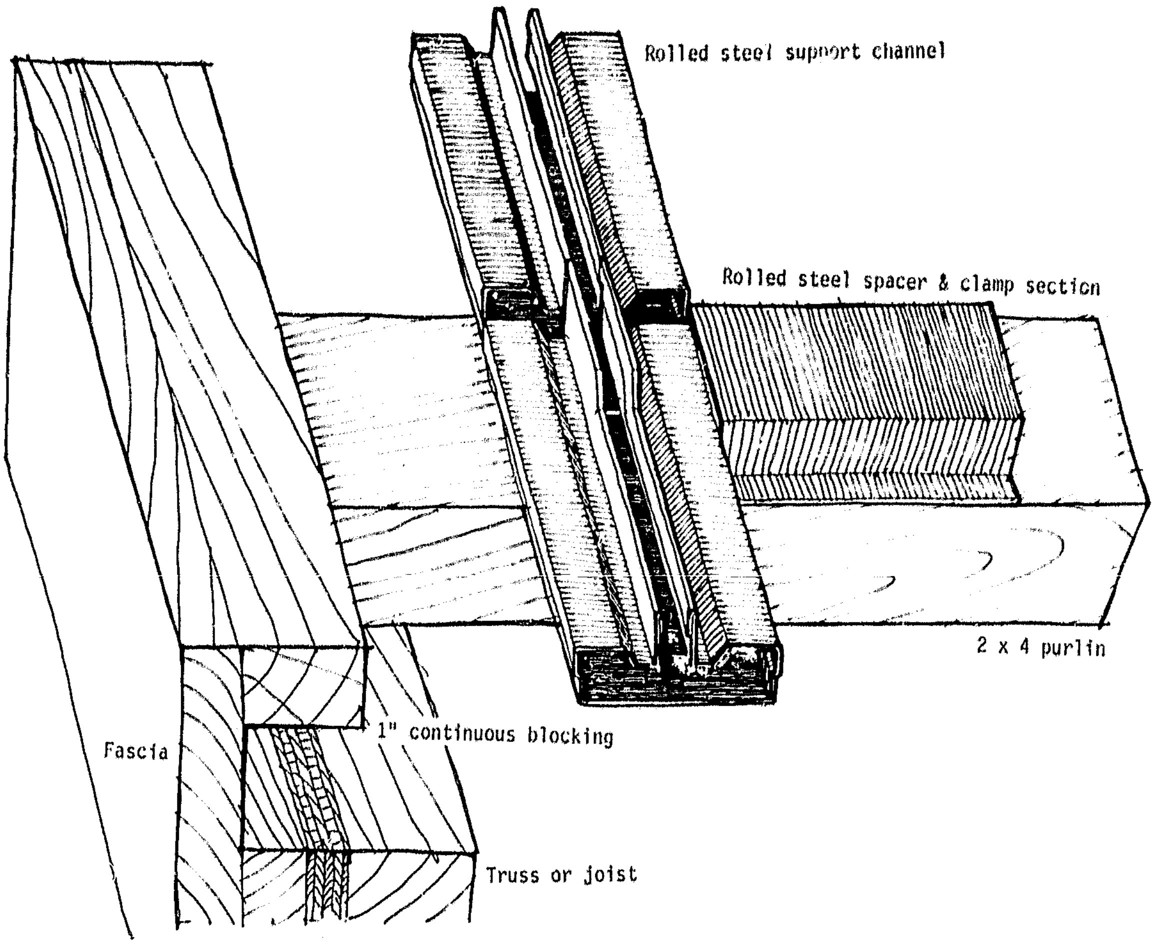
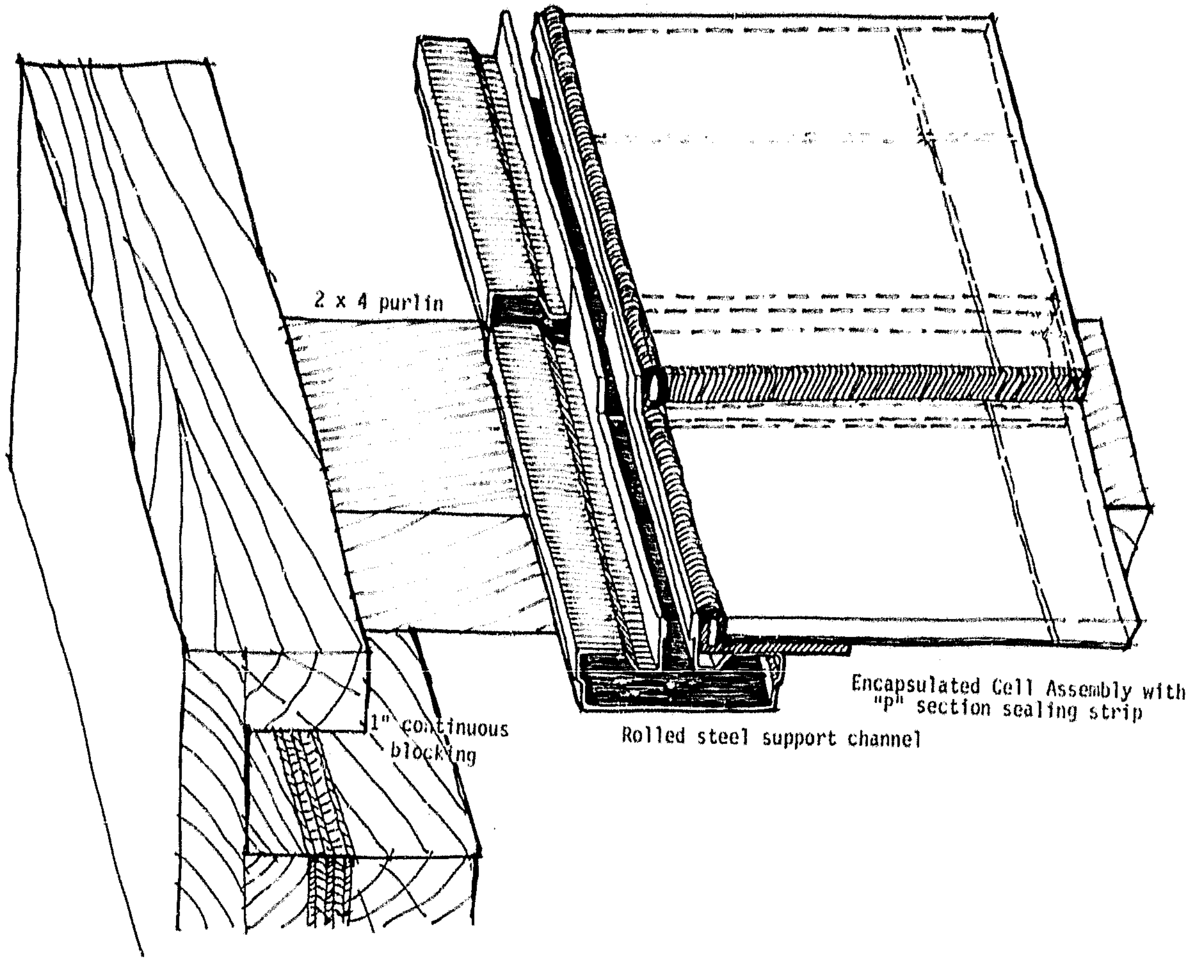
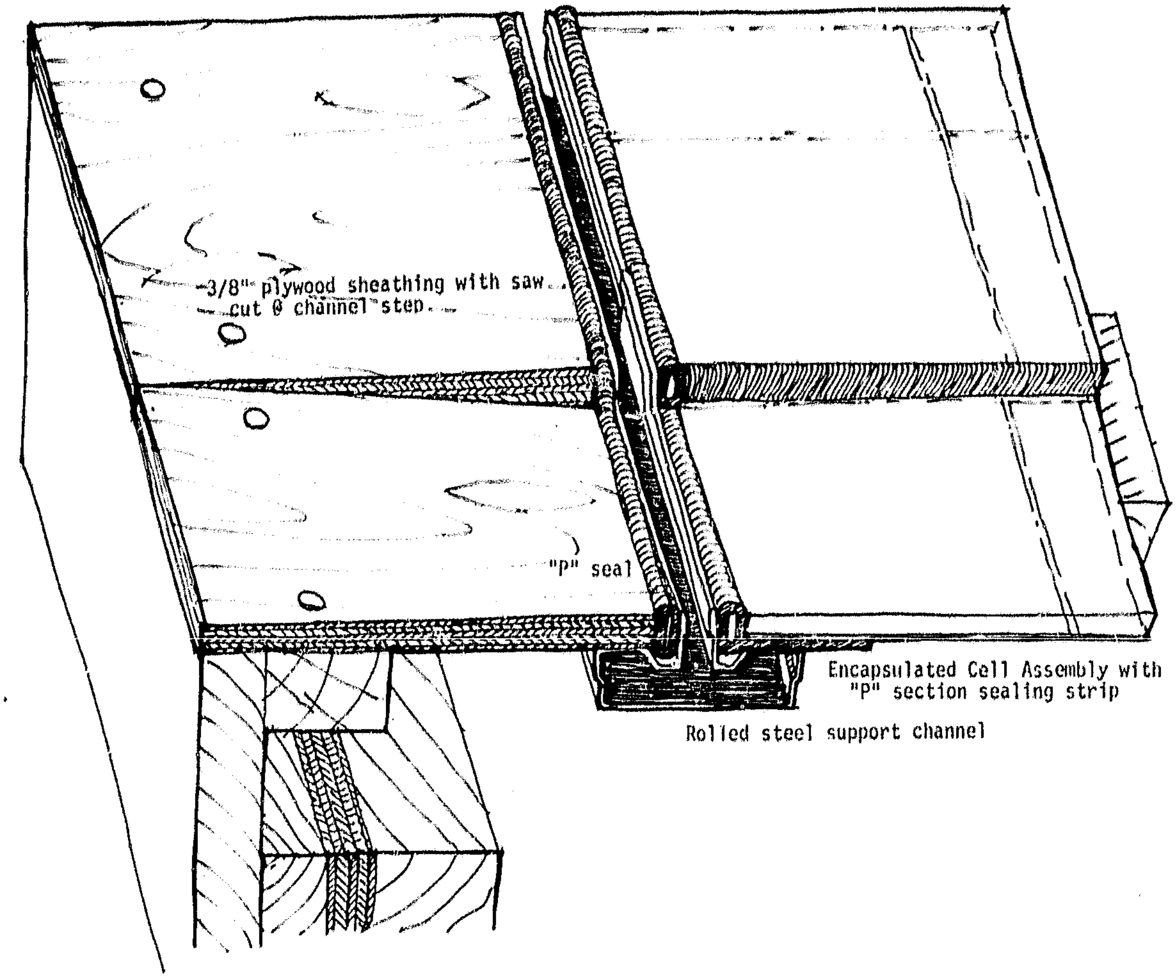
Integral Mount: Rake Detail

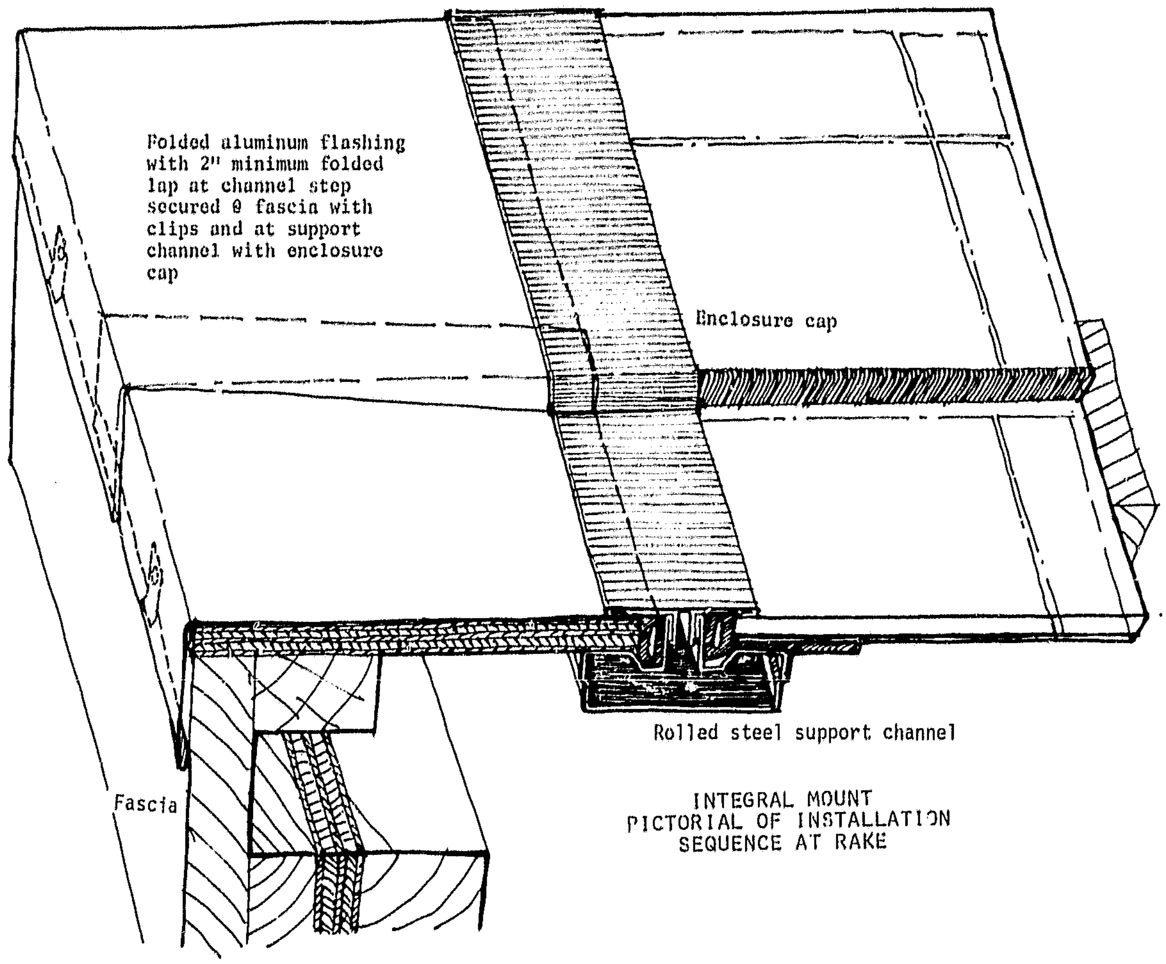


Integral Mount: Installation Sequence at Rake




2 x 4 purlin
1" continuous blocking
Rolled steel support channel
Encapsulated Cell Assembly with "P" section sealing strip

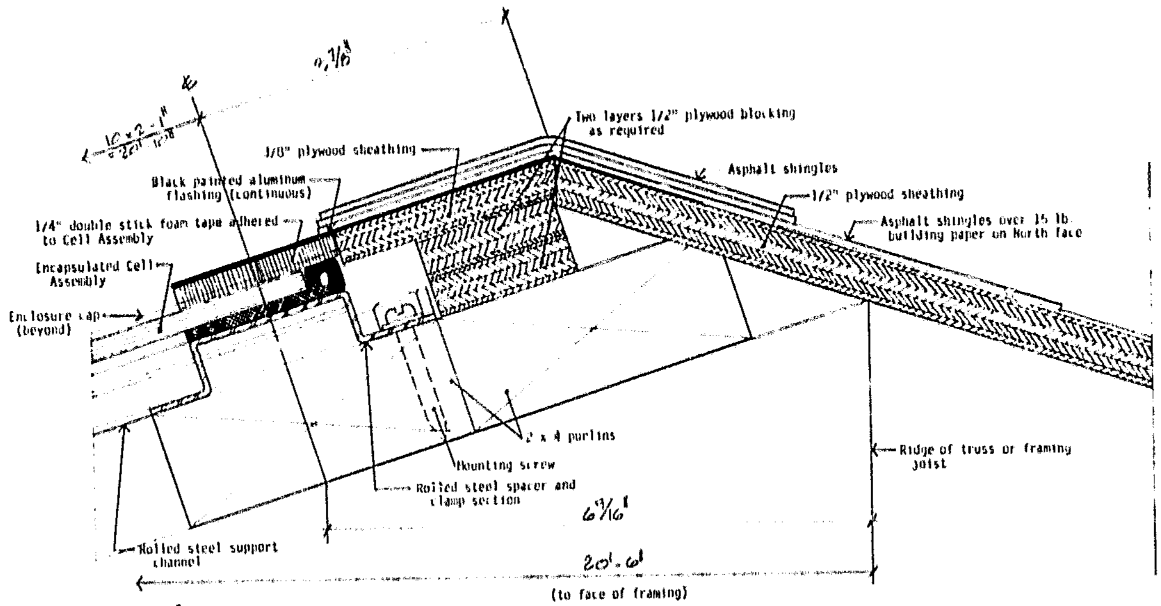

3/8" plywood sheathing with saw cut @ channel step.
"P" seal
Encapsulated Cell Assembly with "P" section sealing strip
Rolled steel support channel



INTEGRAL MOUNT
PICTORIAL OF INSTALLATION
SEQUENCE AT RAKE

C-6

Integral Mount: Ridge Detail



Assumptions

- PLANT OPERATES THREE (3) EIGHT HOUR SHIFTS/DAY, 6 DAYS/WEEK (144 WORK HOURS/WEEK), WITH NINE HOLIDAYS AND ONE WEEK PLANT SHUTDOWN. THIS YIELDS 297 WORKING DAYS/YEAR OR 7128 WORKING HOURS/YEAR.

- PRODUCTION OUTPUT REQUIREMENTS

  50,000 M^2/YEAR = 5,000,000 CELLS/YR =

  69445 MODULES/YR = 9.74 MODULES/HR

- MATERIALS HANDLING AND STORAGE REQUIREMENTS BASED ON WEEKLY DELIVERIES OF INCOMING GOODS PLUS A ONE WEEK SAFETY STOCK

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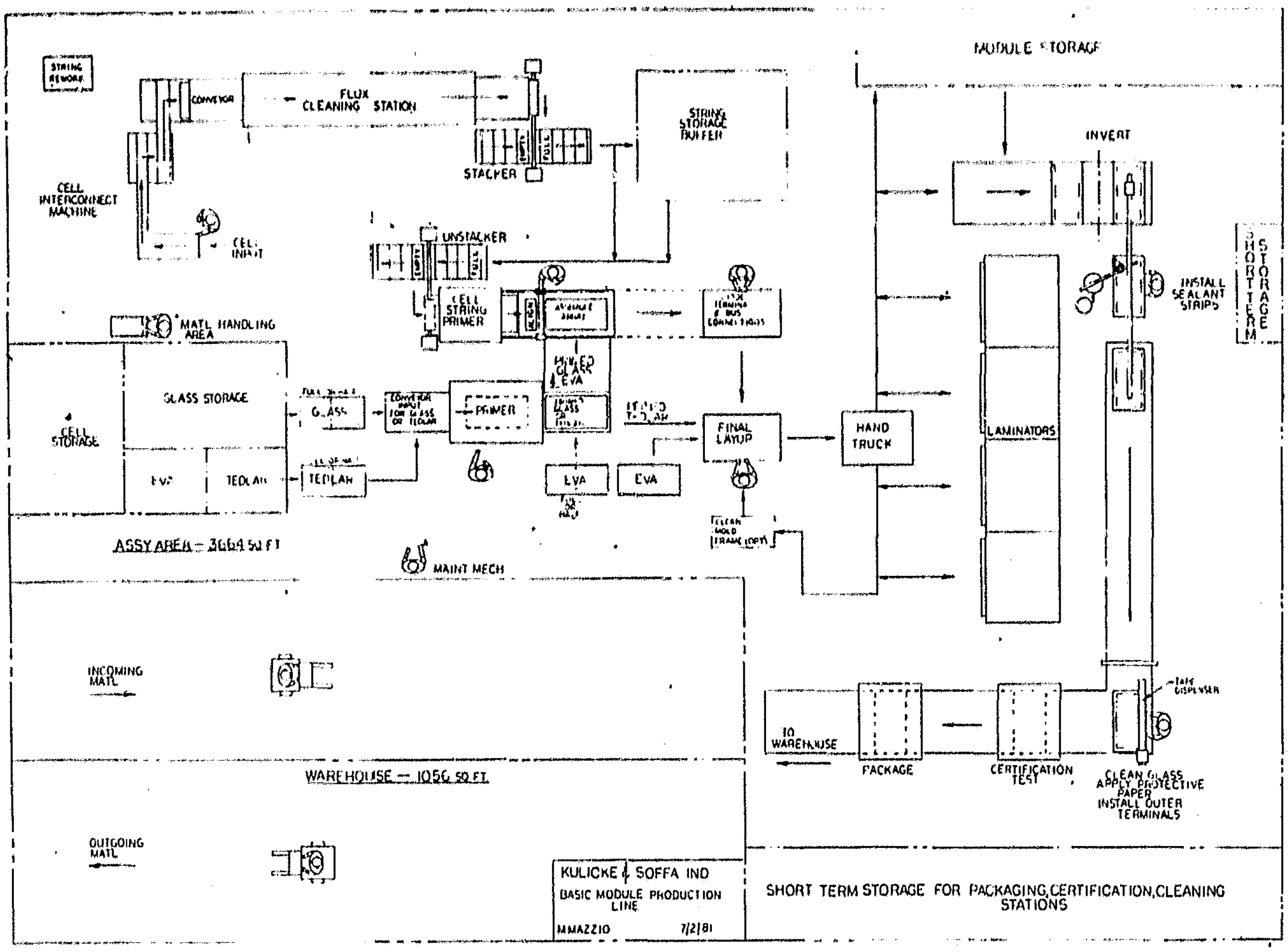
Plant Layout



Production Parameters

PARAMETER	VALUE
MANPOWER (NO. OF EMPLOYEES)	11
FLOOR SPACE (FT^2)	4720
UTILITY SERVICES	
ELECTRICITY (KW)	31.5
AIR (CFM)	6
WATER (GPM)	13.1
EQUIPMENT COST (1980 $)	943,000
PROCESS YIELD (%)	
LAMINATION	98
FINAL ASSEMBLY	99.5

Production Cost Methodology

PRODUCTION COSTS ARE CALCULATED AS THE SUM OF:

1. DIRECT LABOR

$$= \frac{\text{(NO. OF EMPLOYEES)(7128)(1.25)(7.00)}}{\text{(ANNUAL PRODUCTION RATE)}}$$

2. 170 PERCENT LABOR OVERHEAD
3. DIRECT MATERIAL
4. 3 PERCENT MATERIAL OVERHEAD
5. PROCESS EQUIPMENT CHARGE

$$= \frac{\text{(ORIGINAL COST)}}{\text{(5 YRS.)(ANNUAL PRODUCTION RATE)}}$$

6. FLOOR SPACE RENTAL

$$= \frac{\text{(5.50)(FLOOR SPACE REQUIRED - FT}^2\text{)}}{\text{(ANNUAL PRODUCTION RATE)}}$$

7. UTILITY SERVICES

- ELECTRICITY $= \frac{\text{(POWER - kW)(7128)(0.04)}}{\text{(ANNUAL PRODUCTION RATE)}}$
- COMPRESSED AIR FACILITY $= \frac{\text{(cfm)(20)}}{\text{(5 YRS.)(ANNUAL PRODUCTION RATE)}}$
- CHILLED WATER FACILITY $= \frac{\text{(gpm)(17)}}{\text{(5 YRS.)(ANNUAL PRODUCTION RATE)}}$

Production Cost Summary (1980 $/Module)

	Solar Cell Unit Cost (1980 $/Cell)					
	0	1	2	3	4	5
Direct Labor	9.88	9.88	9.88	9.88	9.88	9.88
Labor Overhead (170%)	16.80	16.80	16.80	16.80	16.80	16.80
Cost of Capital Equipment	2.71	2.71	2.71	2.71	2.71	2.71
Cost of Utility Services	0.13	0.13	0.13	0.13	0.13	0.13
Rent for Floor Space	0.37	0.37	0.37	0.37	0.37	0.37
Direct Material	31.48	105.32	179.16	253.00	326.84	400.68
Material Overhead (3%)	0.94	3.16	5.37	7.59	9.81	12.02
Subtotal	62.31	138.37	214.42	290.48	366.54	442.59
Profit and Warranty (20%)	12.46	27.67	42.88	58.10	73.31	88.52
Total Factory FOB Price	74.77	166.04	257.30	348.58	439.85	531.11

Assumptions

- SPECIALTY RESIDENTIAL PHOTOVOLTAIC INSTALLER
- SEVERAL HUNDRED INSTALLATIONS PER YEAR ON A ONE-BY-ONE BASIS FOR INDIVIDUAL CONTRACTORS OR HOMEOWNERS
- ALL WORK PERFORMED BY CARPENTERS, ELECTRICIANS, AND GLAZIERS (NO ROOFERS USED)
- LABOR RATES REFLECT BOSTON WAGE SCALE, WHICH IS ALSO UNION SCALE (USUALLY WITHIN 2% OF THE NATIONAL AVERAGE)
- NON-UNION CREWS ARE ASSUMED SO THAT WORK FLEXIBILITY WITH RESPECT TO TRADES CAN BE MAINTAINED.
- 20% MARK-UP FOR OVERHEAD AND PROFIT
- 40% COMBINED LABOR BURDEN APPLIED

Installation Cost Estimate

	Item Description	Quantity	Units	Unit Price (1980 $)	Total Cost (1980 $)
Material	Closure Strip	62	EA	3.00	186
	Spacer and Clamp Section	57	EA	2.70	154
	Channel	70	EA	3.00	210
	Mounting Screws	2	LB	0.50	1
	P Seal	50	LF	0.30	15
	Double Sided Foam Tape (1/4" x 2")	24	LF	0.54	13
	AMP Solarlok Harness				
	6' Double End	50	EA	2.50	125
	12' Single End	5	EA	3.00	15
	24' Single End	5	EA	4.25	21
	CDX Plywood 3/8" thk	2	SHT	10.00	20
	CDX Plywood 1/2" thk	0.5	SHT	12.50	6
	Purlins (2 x 4 fir)	277	LF	0.24	66
	Flashing - Black Aluminum				
	.032" x 10" x 50'	2	RL	24.00	48
	.032" x 14" x 50'	0.5	RL	34.00	17
	Eave Blocking 2" x 3"	22	LF	0.18	4
	Conduit - 1" Dia	20	LF	0.30	6
	Outlet Box 4" x 4"	2	EA	2.00	4
Labor	Set-up, Purlins, Blocking, Flashing, Plywood Substrate - 10 hrs carpenter and laborer @ $25.20/hr.				252
	Layout, Set Supports, Lay-in Connectors, Set Panels, Set Covers, Check and Caulk -- 4 hrs glazier and carpenter @ $30.80/hr.				123
	Set Outlet Boxes, Connect Panels and Check -- 2 hrs electrician and helper @ $37.00/hr.				74
		Subtotal			1360
		Overhead and Profit (20%)			272
		Warranty			100
		Total Installation Cost			$1732

Cost Summary (1980 $/Module)

	Solar Cell Unit Cost (1980 $/Cell)					
	0	1	2	3	4	5
Module FOB Factory Price	74.77	166.04	257.30	348.58	439.85	531.11
Shipping, Handling, Marketing and Distribution Cost	--	--	--	--	--	--
Installation Cost						
Integral	34.64					
Direct	37.32					
Stand-Off	41.08					
Totals						
Integral	109.41	200.68	291.94	383.22	474.49	565.75
Direct	112.09	203.36	294.62	385.90	477.17	568.43
Stand-Off	115.85	207.12	298.38	389.66	480.93	572.19

INTEGRATED RESIDENTIAL PV ARRAY DEVELOPMENT

AIA RESEARCH CORP.

Objectives

- DEVELOP INTEGRATED ROOF-MOUNTED RESIDENTIAL ARRAY FOR EARLIEST AND LARGEST MARKET PENETRATION.
- OPTIMIZE ARRAY FOR LEAST LIFE CYCLE ENERGY COST ASSUMING ANNUAL PRODUCTION RATE OF 10,000, 50,000, AND 500,000 M2.
- FOLLOW INTEGRATED SYSTEMS APPROACH CONSIDERING DETAILED ELECTRICAL, MECHANICAL, AND ENVIRONMENTAL REQUIREMENTS.
- OPTIMIZE FOR REGIONAL VARIABLES SUCH AS CODES, CONSTRUCTION PRACTICES, AND LOCAL COSTS.
- PREPARE DOCUMENTATION OF FINAL DESIGN SUFFICIENT FOR THIRD-PARTY FABRICATION.
- FABRICATE PROTOTYPE OF DESIGN TO IDENTIFY ADDITIONAL ROOF/ ARRAY INTERFACE CONCERNS.

Program Tasks

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TASK 1

- Convene Advisory Committee to review issues, approve draft of RFP
- Develop and distribute RFP
- Develop LCC data requirements
- Select 8 Firms; Advisory Committee supplies technical assistance
- Advisory Committee selects three best concepts

Task 1 Documented

TASK 2

- Advisory Committee review 3 designs and selects optional design
- Subcontracting firm develop optional design in detail
- Arch. P.V. contractor, manufacturer and LCC consultant provide technical assistance
- Advisory Committee review and approves construction and specification documents

Advisory Committee

AIA/RC, research agency of American Institute of Architects

HEERY, value-engineering A&E firm

EDA, principal investigator Residential PV Module and Array Requirements Study

NAHB/RF, research agency of National Association of Homebuilders

SOLAREX, PV module manufacturer

TASK 3

- Model Fabricator provides full-scale prototypical model based on a representative section based on construction documents

Entire Project Documented for JPL

ENGINEERING AREA AND OPERATIONS AREA JOINT SESSION

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PHASE 1
Summary

OBJECTIVES

DEFINE ARRAY DESIGN TRADE-OFFS

- MARKET PENETRATION
- FABRICATION
- DESIGN AND SPECIFICATION
- INSTALLATION
- OPERATION
- MAINTENANCE

DEVELOP DESIGN REQUIREMENTS FOR CANDIDATE OPTIMUM CONCEPTS

APPROACH

DEVELOP GROUNDRULES AND CRITERIA

GENERATE REPRESENTATIVE DESIGN AND TRADE-OFF DATA

SYNTHESIZE DESIGN TRADE-OFFS

- ANALYSIS
- NORMALIZATION OF SYSTEM AND MODULE SIZE

SCREEN DESIGN TRADE-OFFS

RECOMMEND PREFERRED DESIGN(S) FOR FURTHER OPTIMIZATION

Design Concept Evaluation Criteria

MARKET PENETRATION

- SATISFY THE LARGEST MIDDLE-INCOME MASS MARKET
- SERVE A VARIETY OF HOUSING SIZES, TYPES AND ROOF SHAPES
- SELECTION BY BOTH LARGE AND SMALL VOLUME BUILDERS
- FLEXIBILITY IN INSTALLATION TIMING
- WITHIN THE TYPICAL PRODUCT DELIVERY AND SERVICE CHAIN OF THE HOMEBUILDING INDUSTRY

FABRICATION

- MIXTURE OF FACTORY AND FIELD LABOR FOR ARRAY ASSEMBLY
- REQUIREMENTS FOR COMPONENT INVENTORY
- MINIMIZE THE COST FOR SHIPPING AND HANDLING WITH ACCEPTABLE DURABILITY

DESIGN AND SPECIFICATION

- DESIGN ENGINEERING CAPABILITY NORMALLY EMPLOYED BY THE BUILDER OR CONTRACTOR
- MINIMIZE FIELD INSPECTION AND APPROVAL REQUIREMENTS OF LOCAL BUILDING AND ZONING CODES, THE NATIONAL ELECTRICAL CODE (NEC), FIRE CODES AND INSURANCE WARRANTS
- USE OF EQUIVALENT MATERIALS AND PRODUCTS IN STANDARD CONSTRUCTION PRACTICE
- FLEXIBILITY IN LABOR AND SCHEDULE COORDINATION THAT MEETS STANDARD PRACTICE CONDITIONS
- DOCUMENTATION FOLLOW STANDARD PRACTICE

INSTALLATION

- LITTLE IMPACT ON THE NORMAL STRUCTURAL AND ENVIRONMENTAL EXPOSURE OF THE BUILDING
- COMPATIBLE WITH STANDARD CONSTRUCTION PRACTICES, TOOLS AND EQUIPMENT
- MINIMIZE FIELD APPROVAL OF ELECTRICAL CONNECTIONS, FIELD CABLING AND GROUNDING
- MINIMIZE SAFETY RISK DURING INSTALLATION
- OPTIMIZE HANDLING AND INSTALLATION DURABILITY
- OPTIMIZE MECHANICAL ATTACHMENT AND ELECTRICAL CONNECTION REQUIREMENTS

OPERATION

- AN ACCEPTABLE OUTPUT RANGE FOR SIZE AND TEMPERATURE CONDITIONS
- ARRAY OUTPUT MUST SATISFY BALANCE OF SYSTEM INTERFACE REQUIREMENTS
- MINIMIZE GROUNDING CONCERNS AND REQUIREMENTS
- ADDRESS APPROPRIATE POWER AND DIMENSIONAL MODULARITY CONCERNS
- LIFETIME RELIABILITY AND DURABILITY CONDITIONS AT AN ACCEPTABLE COST

MAINTENANCE

- MINIMIZE THE REQUIREMENTS FOR IDENTIFICATION, REMOVAL AND REPLACEMENT OF FAILED PARTS
- NOT INTERFERE WITH NORMAL BUILDING MAINTENANCE AND REPAIR
- MINIMIZE ADDED LIFE SAFETY AND BUILDING RISKS

Ground Rules

CELL AND ENCAPSULATION PROCESSING BEYOND SCOPE OF STUDY

ENCAPSULATED CELL EFFICIENCY OF 135 W_p/m^2 AT 100 mW/cm^2, AM 1.5, 28°C

GLASS ENCAPSULATED MODULE COST OF $0.70/$W_p$ IN $1980

EXCESSIVE HOT-SPOT HEATING PREVENTED

V_{OC} LESS THAN 30 Vdc AT -20°C FOR MODULES/PANELS WITH EXPOSED TERMINALS

ARRAY IS PV-ONLY,AIR-COOLED, FLAT-PLATE, SOUTH-FACING WITH FIXED TILT

ARRAY DESIGN LIFE IS 20 YEARS

ONE MODULE REPLACEMENT EVERY FOUR YEARS

ARRAY OUTPUT BETWEEN 4-10 kW_p

USE OF REGIONAL CODE LOADS

ARRAY DESIGN AND INSTALLATION WITHIN STANDARD BUILDING PRACTICES

INITIAL COSTS ONLY CONSIDERED IN PHASE 1

LIFE CYCLE COSTS WITH 6% DISCOUNT RATE CONSIDERED IN PHASE 2

DESIGN TEAM SPECIFIES MARKET AND DISTRIBUTION ASSUMPTIONS FOR EARLIEST AND LARGEST PENETRATION

TECHNOLOGY PROVEN NOT LATER THAN 1982

Summary of Design Concepts

MOUNTING TYPE	DESCRIPTION	SAMPLE N = 16	OUTPUT Wp	AREA M^2	TOTAL \$/Wp	HARDWARE \$/Wp	WIRING \$/Wp	CREDITS \$/Wp
INTEGRAL	EIGHTEEN (18) UNFRAMED PANELS/MODULES ARE PRESSURE FITTED IN A "T" SHAPED NEOPRENE GASKET GRID AND SEALED BY A ZIPLOCKING STRIP. THE GASKET GRID IS PRESSURE FITTED INTO AN ALUMINUM CHANNEL EXTRUSION GRID THAT IS SCREWED DIRECTLY TO THE RAFTERS.	1	4455	41.43	1.31	0.50	0.03	C.13
	TEN (10) FRAMED PANELS EACH MADE FROM TWO EXTRUDED ALUMINUM CARRIAGE PIECES JOINED BY LATERAL ANGLES ARE BOLTED TO THE RAFTERS. EACH OF THE NINE (9) MODULES PRESSURE FITTED IN A PANEL OVERLAPS THE LOWER ONE AND IS HELD IN PLACE BY A LAP BAR.	2	9760	76.2	1.41	0.70	0.13	0.30
	EIGHTY (80) FRAMELESS MODULES ARE SEALED USING A SILICONE ADHESIVE TO A PREFABRICATED GRID OF RIGID TAPE AND SHEET METAL BOLTED TO THE RAFTERS.	3	9990	78.1	1.07	0.23	0.04	0.11
	FORTY (40) GASKETED MODULES ARE SEALED IN A SET OF PREWIRED MOUNTING CHANNELS NAILED ALONG THE LENGTH OF THE RAFTERS.	4	9990	78.1	1.11	0.27	0.04	0.11
	TWENTY-FOUR (24) UNFRAMED MODULES ARE PRESSURE FITTED BETWEEN A SERIES OF EXTRUDED ALUMINUM BATTEN STRIPS AND PLYWOOD SUPPORT STRIPS MOUNTED DIRECTLY TO THE RAFTERS. WATERPROOF SEAL IS PROVIDED BY BUTYL GLAZING TAPE AT THE TOP AND SIDES OF THE MODULES.	5	4200	50.5	1.10	0.40	0.06	0.17
DIRECT	FIFTY-SIX (56) UNFRAMED MODULES ARE PRESSURE FITTED IN A GRID OF THERMOPLASTIC "T" AND "I" SHAPED GLAZING GASKETS THAT ARE SCREWED TO THE ROOF SHEATHING. THE "I" SHAPED SECTIONS HAVE BEEN COEXTRUDED WITH EMBEDDED BUSBARS FOR MODULE PARALLEL WIRING. EACH MODULE RESTS ON A RIBBED PLASTIC BACKING SHEET.	6	9250	83.3	1.10	0.20	0.05	0.06
	EIGHTY (80) FRAMELESS MODULES ARE SEALED BY A SILICONE ADHESIVE IN A PREFABRICATED GRID OF RIGID TAPE AND SHEET METAL ATTACHED TO THE ROOF.	7	9990	78.1	1.13	0.23	0.04	0.05
	FORTY (40) GASKETED MODULES ARE SEALED IN A SET OF PREWIRED MOUNTING CHANNELS MECHANICALLY FASTENED TO THE ROOF.	8	9990	78.1	1.18	0.27	0.04	0.05

MOUNTING TYPE	DESCRIPTION	SAMPLE N = 16	OUTPUT Wp	AREA M^2	TOTAL $/Wp	HARDWARE $/Wp	WIRING $/Wp	CREDITS $/Wp
STANDOFF	FORTY (40) UNFRAMED MODULES ARE PRESSURE FITTED IN A SERIES OF ZIPPERLOCKING EPDM RUBBER EXTRUSIONS ADHESIVELY BONDED TO THE ROOF SURFACE.	9	5158	59.5	1.22	0.30	0.01	0
	EIGHTEEN (18) FRAMED ANS SEALED PANEL/MODULES ARE FASTENED TO 30 UNEQUAL LEG "T" SHAPED BRACKETS BOLTED TO THE RAFTERS.	10	4275	45.81	1.52	0.59	0.02	0
	TWELVE (12) ALUMINUM FRAMED PANELS WITH LATERALLY SUPPORTING "T" STRUTS ARE CLAMPED TO A STANDING SEAM INSULATED METAL ROOF DECK MOUNTED ON THE RAFTERS.	11	7800	76.7	2.55	1.77	0.19	0.31
	FORTY-TWO (42) UNFRAMED MODULES ARE PRESSURE FITTED IN A SERIES OF ZIPPER-LOCKING EPDM RUBBER EXTRUSIONS THAT ARE ADHESIVELY BONDED TO THE ROOF SURFACE.	12	5860	67.6	1.15	0.24	0.01	0
	TWENTY-FOUR (24) FRAMED PANELS/MODULES ARE PRESSURE FITTED IN FIVE (5) "T" SHAPED TRACKS ALONG THE LENGTH OF THE ROOF.	13	4400	36.8	1.74	0.73	0.04	0
	EIGHTY (80) GASKETED MODULES ARE PRESSURE FITTED BETWEEN A SERIES OF PVC HOLD DOWN CAPS AND EXTRUDED ALUMINUM CHANNELS FASTENED TO THE ROOF.	14	6648	59.7	1.63	0.25	0.23	0
	EIGHTY (80) GASKETED MODULES ARE MOUNTED OVER A SERIES OF CONTINUOUS METAL PANS AND PRESSURE FITTED IN STEEL BATTENS FASTENED TO THE ROOF.	15	8360	74.7	.71	0.47	0.18	0.06

ENGINEERING AREA AND OPERATIONS AREA JOINT SESSION

Critical Factors

- MINIMIZE NEED FOR GROUNDING
  - NON-CONDUCTIVE SURFACES
  - UNEXPOSED TERMINATIONS
- SQUARE OR RECTANGULAR CELLS FOR IMPROVED PACKING DENSITY
- WRAPAROUND TECHNOLOGY DEVELOPMENT AND SERIES/PARALLELING FOR RELIABILITY
- MODULE EDGE TOLERANCES FOR HANDLING AND ATTACHMENT
- UNFRAMED, GASKETED MODULES
- SYSTEM INTERFACE
  - EXISTING INVERTER VOLTAGE WINDOW
  - FUTURE FAMILIES OF INVERTERS
  - CIRCUIT DESIGN FOR MODULE MISMATCH
- SAFETY AND CODE INSPECTION

Concept Evaluation

- CONCEPTS CLASSIFIED FOR COMPARISON IN THREE CATEGORIES
- CONCEPTS EVALUATED WITHIN EACH CATEGORY FOR SELECTION

EVALUATION CATEGORIES	CATEGORY ELEMENTS	EVALUATION CONCERNS
Proof-of-Concept Stage	Off-the-Shelf Pilot Prototype	Concept Development Structural, Life Safety, Durability, and Environmental Testing Field Application
Innovative Features	Module Design Wiring Installation	Minimize Labor/Material Ensure Reliability Improve Efficiency Assure Safety
Mounting System	Integral Direct Standoff Rack	Weather Protection Roof Load Support Modular Array-Edge Support

Proof-of-Concept Stage

OFF-THE-SHELF CONCEPTS

Prototype development completed

Prototype testing completed

Field applications within one year

PILOT CONCEPTS

Prototype development near completion

Prototype testing required

Field applications within two years

PROTOTYPE CONCEPTS

Prototype development continuing

Prototype testing required

Field applications within four years

Innovative Design Features

MODULE DESIGN

- MODULE AREA GREATER THAN $1M^2$
- SQUARE OR RECTANGULAR CELLS
- REDUNDANT PROTECTION FOR MODULE

  OPEN-CIRCUIT VOLTAGES OVER 30 Vdc at -20°C
- MINIMIZED GROUNDING
- LOW SOILING COVER MATERIAL
- SERIES/PARALLELING AND DIODE PROTECTED RELIABILITY

WIRING

- WIRING HARNESS ELIMINATION
- PRE-WIRED MOUNTING HARDWARE
- MINIMIZED WIRE SIZE AND INSULATION
- SERIES/PARALLELING RELIABILITY FOR MODULE MISMATCH AND SYSTEM INTERFACE

INSTALLATION

- HARDWARE APPLICABLE TO SEVERAL MOUNTING TYPES
- MINIMIZED INDIVIDUAL MODULE/PANEL ALIGNMENT
- MECHANICAL FASTENING REPLACEMENT
- PRE-CUT MATERIALS
- MINIMIZED CONSTRUCTION-TRADE LIMITS
- LIMIT MODULE/PANEL ROWS TO MINIMIZE MOUNTING FRAME COMPLEXITY

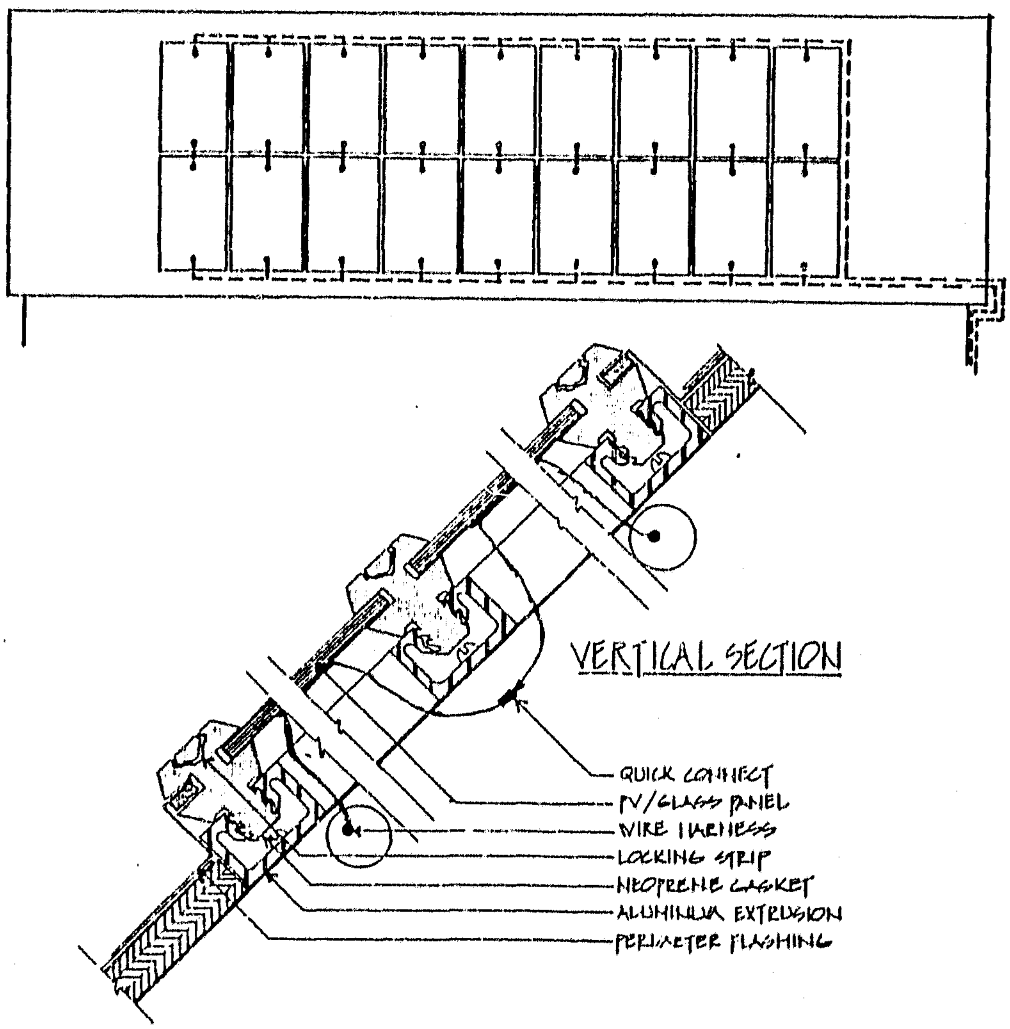
Mounting Types

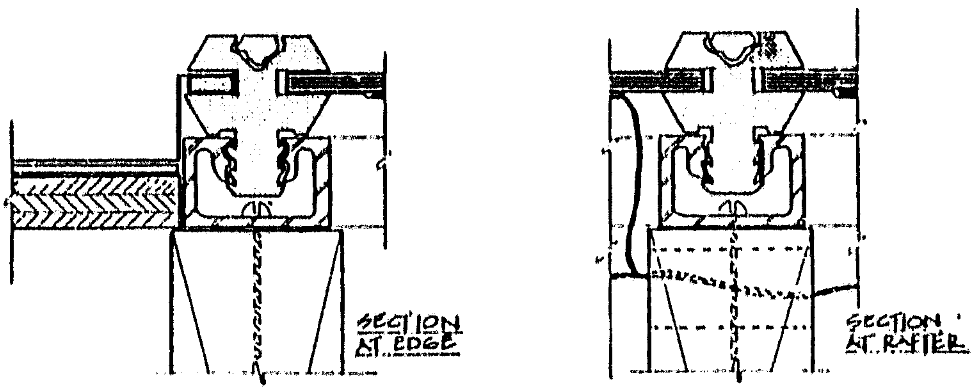
ELEMENT	INTEGRAL	DIRECT	STANDOFF	RACK
WEATHER PROTECTION	PRIMARY WEATHER PROTECTION REPLACED	PRIMARY WEATHER PROTECTION REPLACED	NO WEATHER PROTECTION REPLACEMENT	NO WEATHER PROTECTION REPLACEMENT
STRUCTURAL STABILITY	LATERAL ROOF-LOAD SUPPORT REPLACED	LATERAL ROOF-LOAD SUPPORT NOT REPLACED	LATERIAL ROOF-LOAD SUPPORT NOT REPLACED	ROOF-LOAD SUPPORT MAY BE REQUIRED
MODULE EDGE SUPPORT	MODULAR ARRAY-EDGE SUPPORT REQUIRED	MODULAR ARRAY-EDGE SUPPORT MAY BE REQUIRED	MODULAR ARRAY-EDGE SUPPORT MAY BE REQUIRED	MODULAR ARRAY-EDGE SUPPORT REQUIRED

Concept Selection

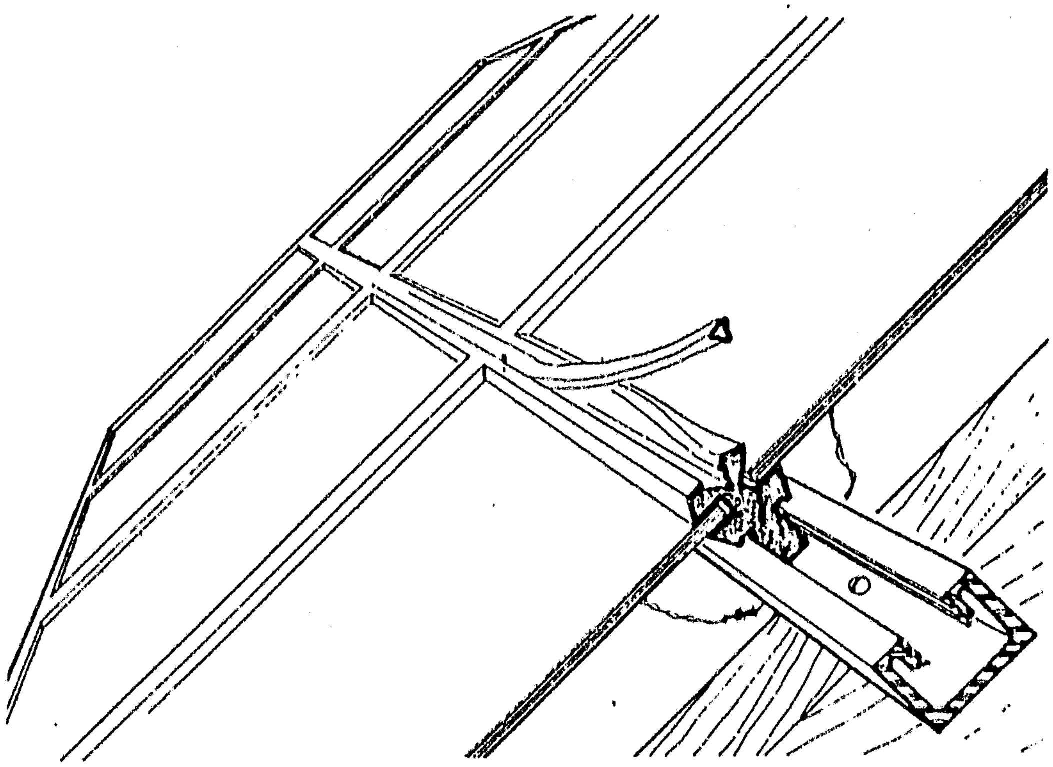
CONCEPT TEAM	PROOF-OF-CONCEPT STAGE	MOUNTING SYSTEM	ARRAY SIZES	MODULE SIZES	INNOVATIVE FEATURES
TOTAL ENVIRONMENTAL ACTION (TEA)	OFF-THE SHELF	INTEGRAL	4455 4608	4 FT X 8 FT 2 FT X 4 FT	LABOR/MATERIAL TRANSFER FROM CURRENT TECHNOLOGY BASE
BURT HILL KOSAR RITTELMANN ASSOCIATES (BHKRA)	PILOT	INTEGRAL DIRECT	9990 5038	2 FT X 5 FT 2 FT X 4 FT	DUAL MOUNTING APPLICATION MINIMUM MODULE ALIGNMENT
ONE DESIGN INC (ODI)	PROTOTYPE	STANDOFF	5158 5227	4 FT X 4 FT 2 FT X 4 FT	WIRING HARNESS ELIMINATION

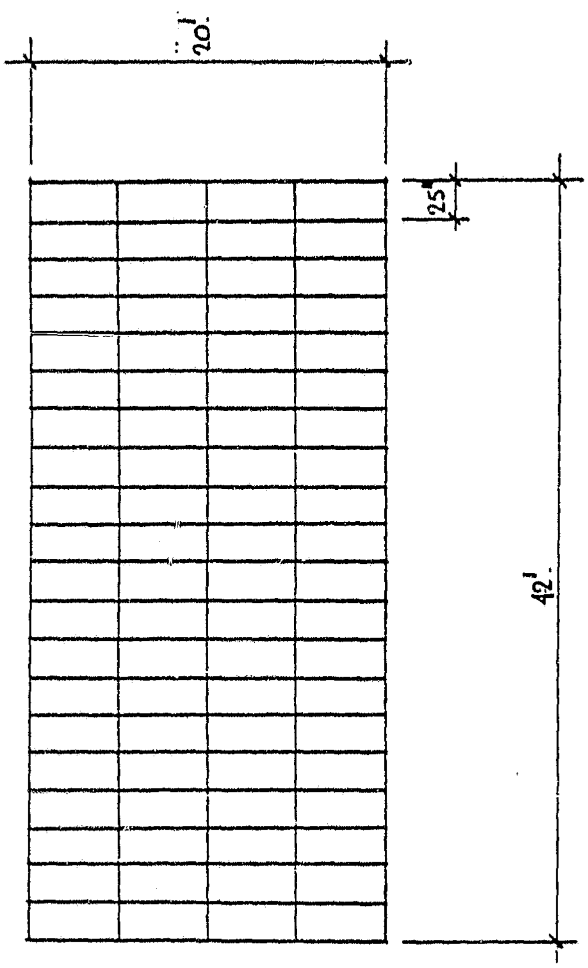
TEA Design Concept

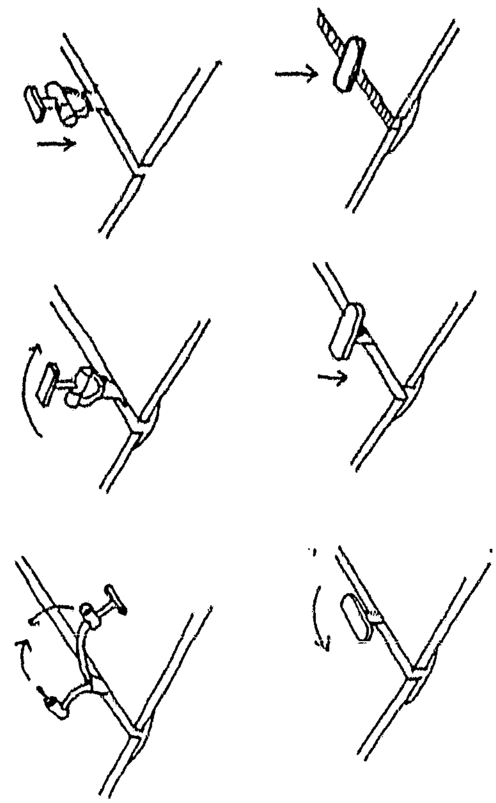


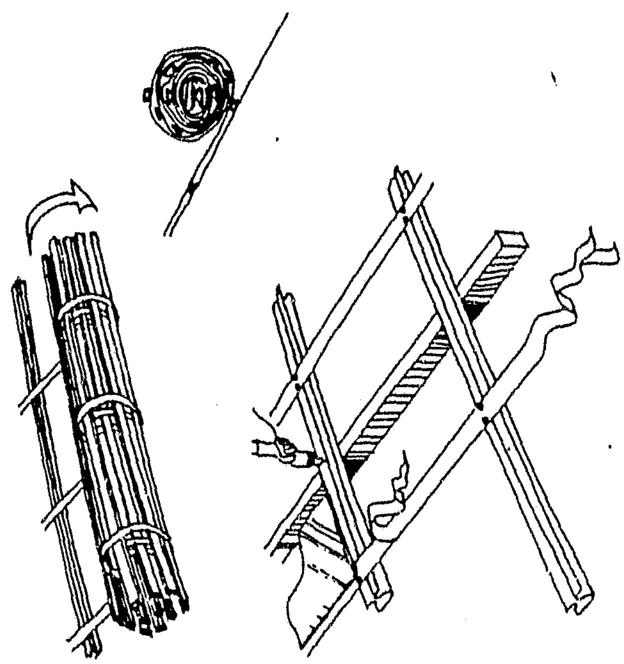


HORIZONTAL SECTION

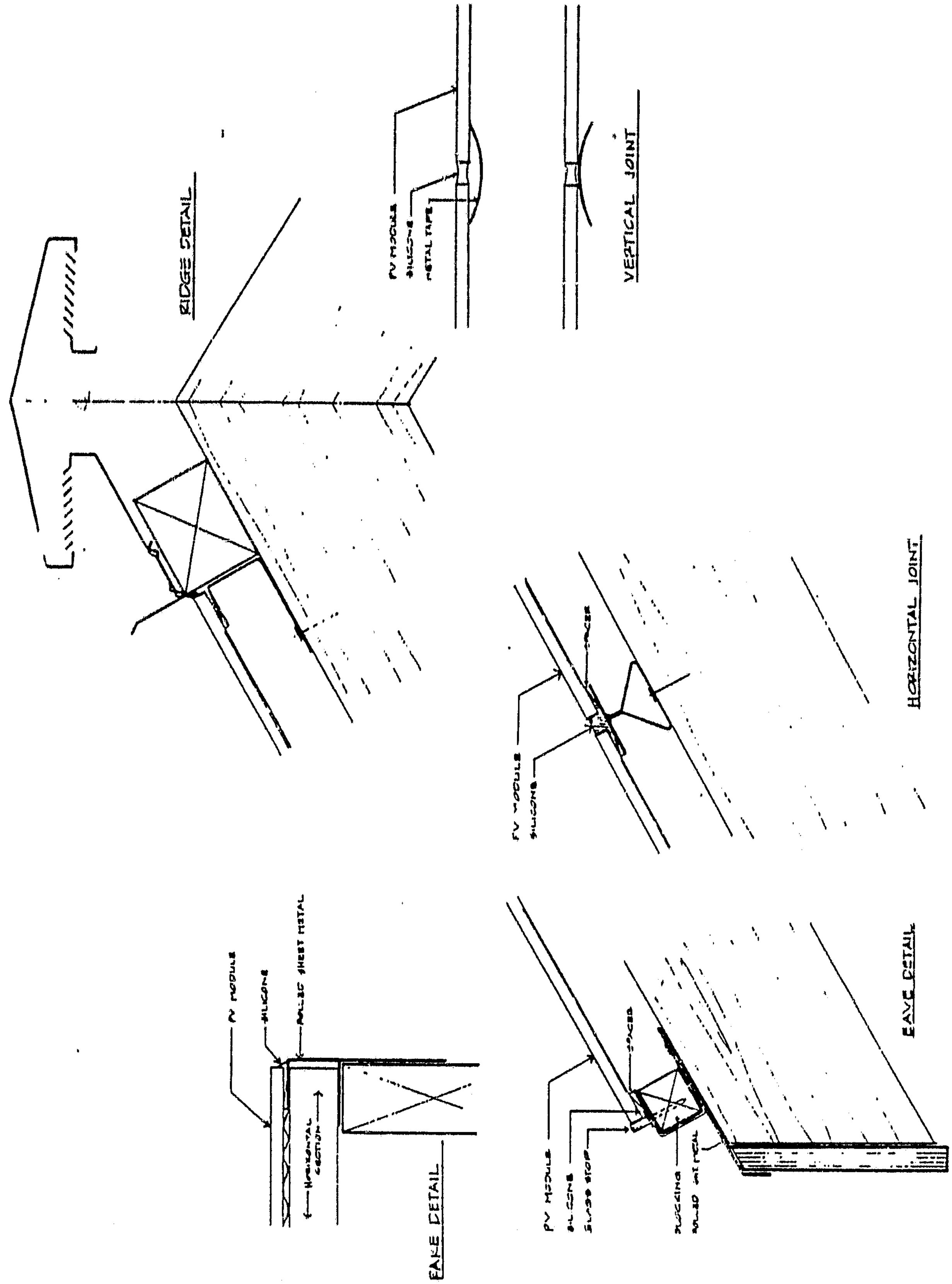


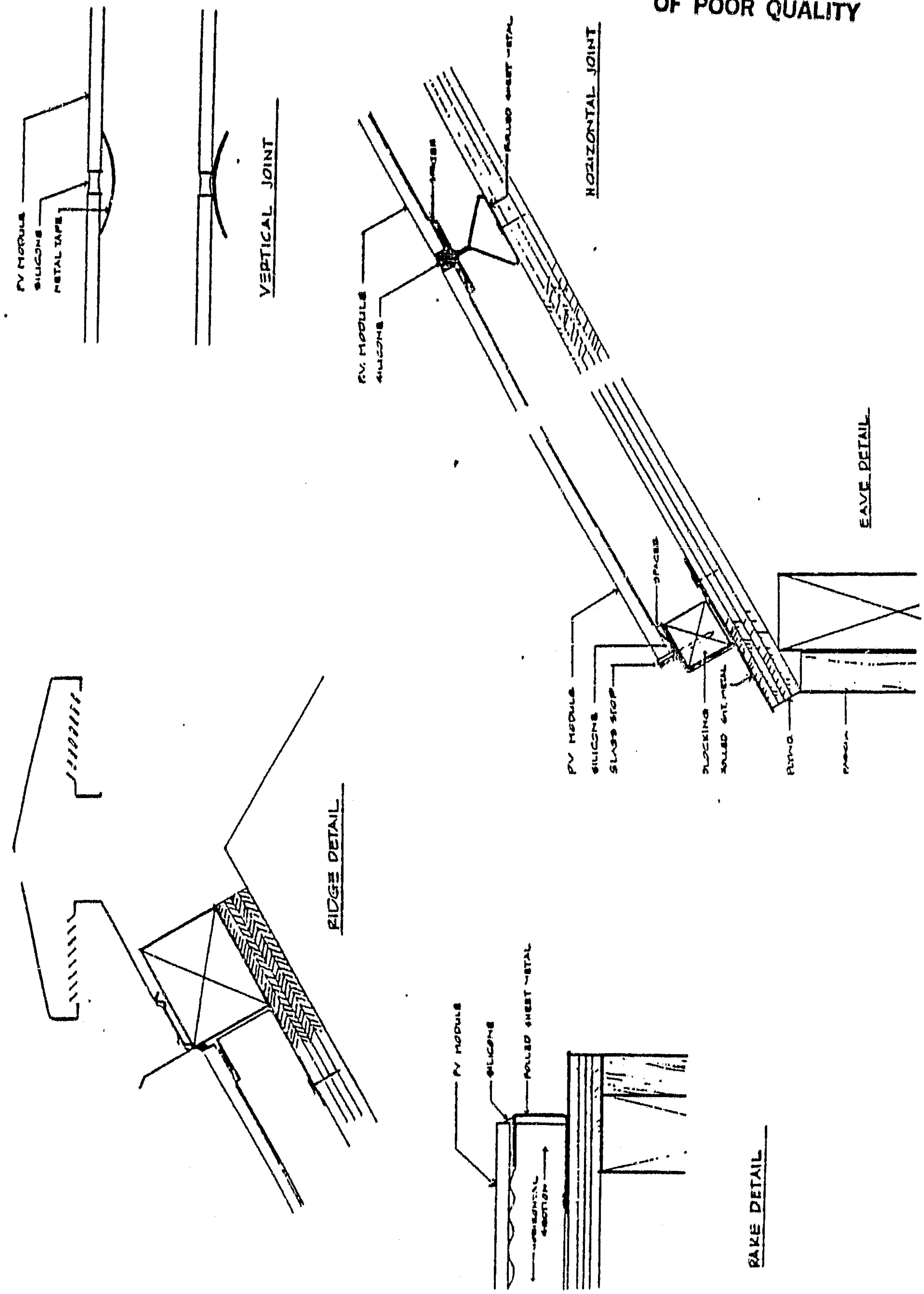

20'
25"
42'



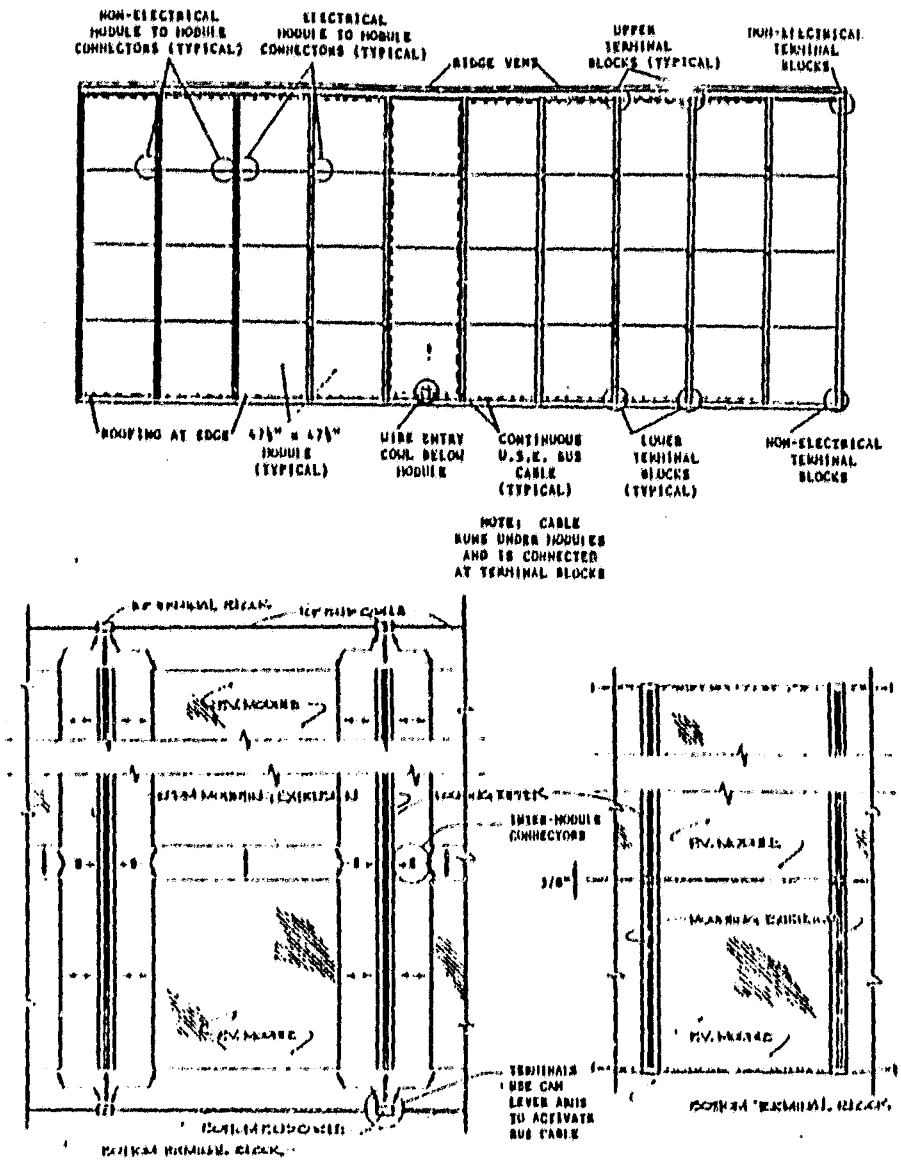


BHKRA Design Concept




PV MODULE
SILICONE
METAL TAPE
VERTICAL JOINT
HORIZONTAL JOINT
EAVE DETAIL
RIDGE DETAIL
RAKE DETAIL

ODI Design Concept



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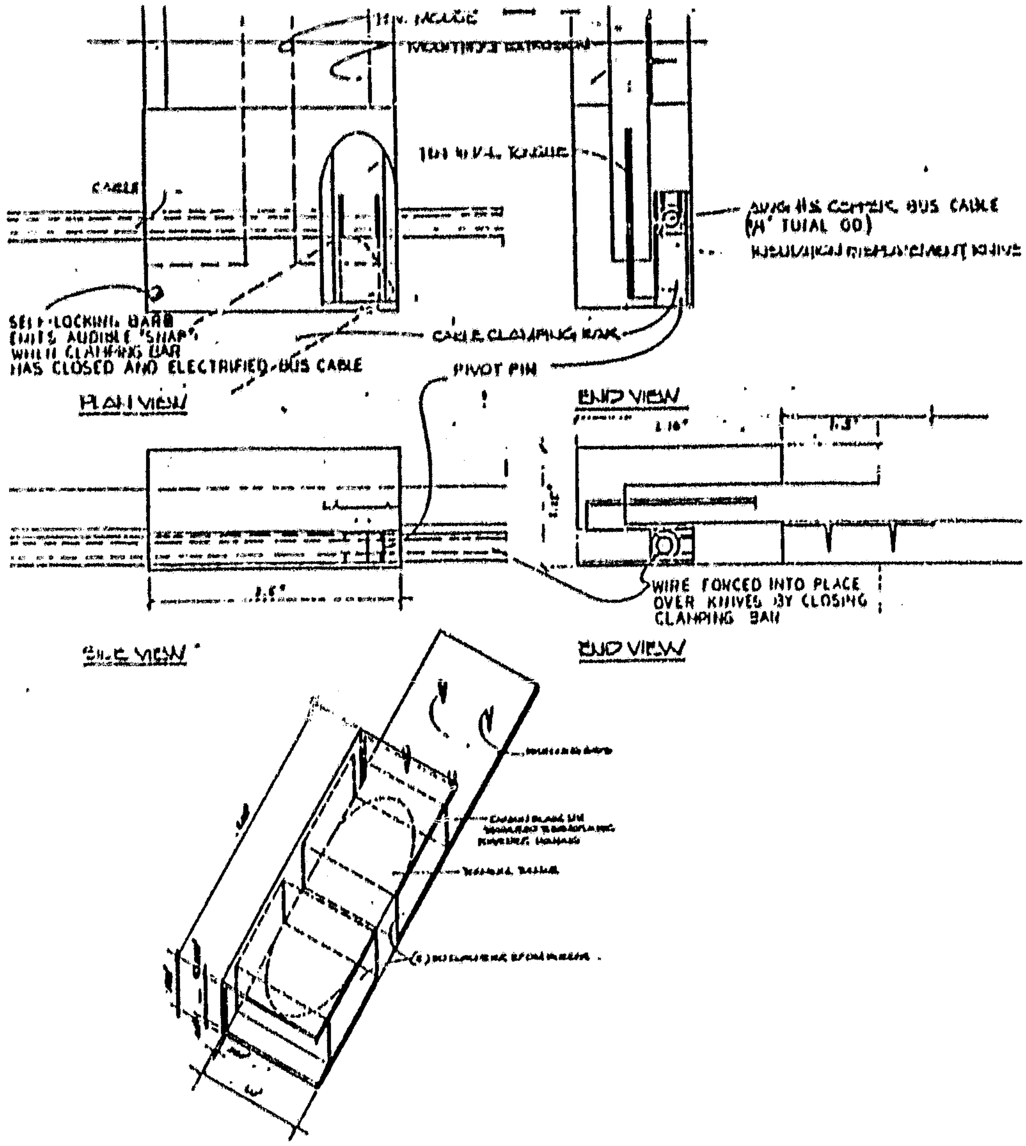
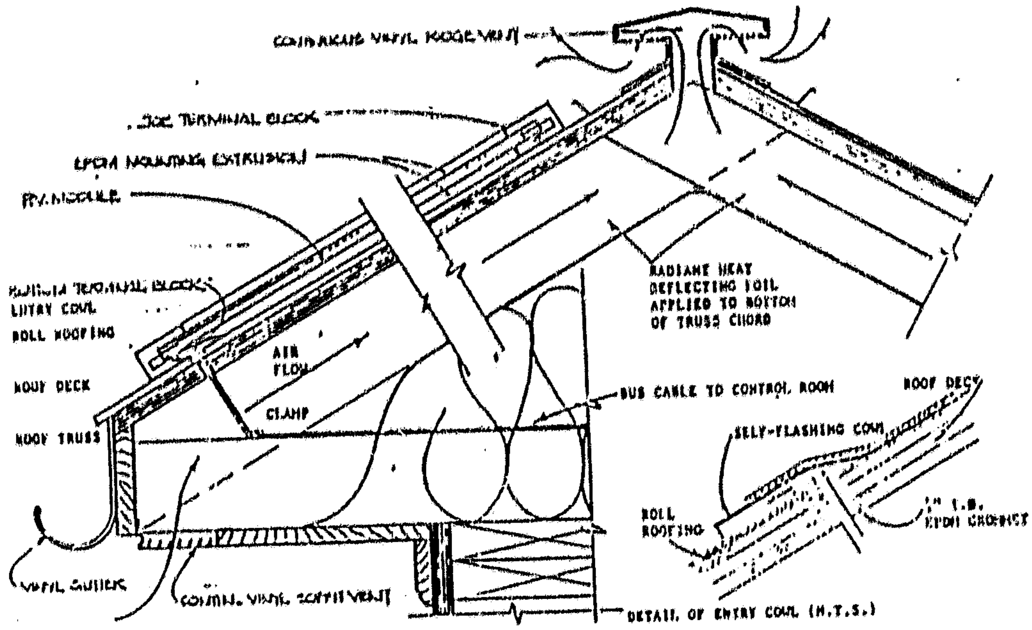




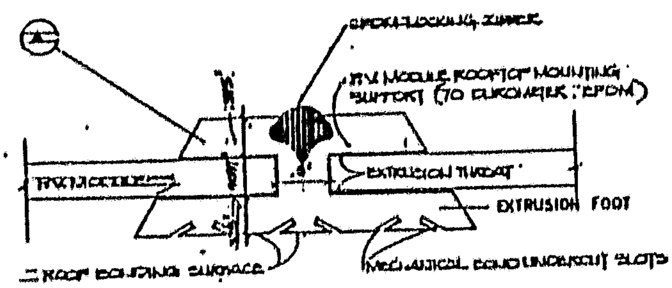


FIG A-1 - CENTER EXTRUSION

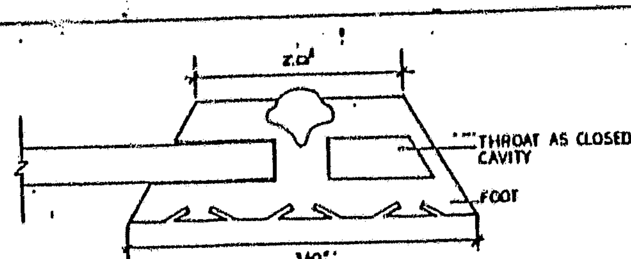


FIG-A-1a - ARRAY END EXTRUSION

Selected Concepts Cost Summary

COST ELEMENT	AVG. SYSTEM COST ($/$W_p$)			DESIGN CONCEPT COST ($/$W_p$, 1980)					
	INTEGRAL	DIRECT	STAND-OFF	NO. 1		NO. 7		NO. 9	
				PHASE 1	PHASE 2	PHASE 1	PHASE 2	PHASE 1	PHASE 2
Array Installation Total	0.40	0.23	0.44	0.45	0.52	0.23	0.25	0.30	0.29
Sealants	0.03	0.02	0.00		0.04	0.04	0.03	0.01	
Flashing	0.04	0.03	0.00	0.04	0.04	0.03	0.03		
Mounting HDWR/Glazing Gaskets	0.20	0.09	0.26	0.16	0.17	0.07	0.06	0.13	0.14
Field Assembly	0.13	0.09	0.17	0.26	0.27	0.09	0.11	0.16	0.16
Shop Assembly	0.00	0.01	0.00			0.02	0.01		
Roof Work	0.02		0.16	0.05	0.05				
Wiring Total	0.06	0.05	0.11	0.03	0.06	0.04	0.08	0.01	0.01
Harnesses	*				0.02		0.05		
Connectors					0.03		0.03		0.01
Busbar(s)					0.01		0.00		0.00
Modules	0.89	0.91	0.98	0.91	0.91	0.91	0.92	0.91	0.91
Standard Roof Credit	0.17	0.05	0.06	0.13	0.16	0.05	0.07		
Net Installed Cost with Modules	1.21	1.24	1.63	1.31	1.14	1.13	1.18	1.22	1.21
without Modules	0.32	0.33	0.65	0.40	0.47	0.22	0.26	0.31	0.30
Replacement Total ($/Module)					95.00		46.52		103.26
Minor Upkeep ($/Yr.)					17.00		75		30.00

PHASE 2
Summary

OBJECTIVES

DEFINE ARRAY DESIGN TRADE-OFFS

- MODULE GEOMETRY AND CIRCUIT DESIGN
- ARRAY ALIGNMENT AND ATTACHMENT
- ARRAY CONNECTION AND CABLING

DEVELOP DESIGN REQUIREMENTS FOR PREFERRED OPTIMIZED CONCEPT

APPROACH

DEVELOP CRITERIA AND METHODOLOGY FOR DESIGN TRADE-OFF ANALYSIS

GENERATE REPRESENTATIVE DESIGNS AND TRADE-OFF DATA

SYNTHESIZE DESIGN TRADE-OFFS

- ANALYSIS
- PROTOTYPING

SCREEN DESIGN TRADE-OFFS

RECOMMEND PREFERRED DESIGN FOR FABRICATION

Detailed Optimization Focus

Module Production
- module geometry
- circuit design
- production rates

Hardware Fabrication
- mounting attachment
- connectors
- pre-wiring
- production rates

Shipping, Handling and Distribution
- modules
- hardware
- end-use economies-of-scale

Installation and Specification
- system size
- module size
- builder profiles

Operation and Maintenance
- startup/shutdown
- minor upkeep
- diagnostics
- replacement

Design Tradeoffs

MODULE HANDLING SIZE REQUIREMENTS

HANDLING BY 1 OR 2 PERSONS
- ANTHROPOMETRIC LIMITS FOR LIFT AND TORQUE

CONFIGURATIONS BETWEEN 1 FT^2 AND 40 FT^2

GLASS ENCAPSULATION SYSTEMS
- EDGE TOLERANCE

MODULE SUPPORT SIZE REQUIREMENTS

MODEL CODE SERVICE LOADS

SUPPORT OPTIONS
- SIMPLE 4-SIDE
- UNIFORM

GLASS THICKNESS

MODULE CIRCUIT SIZE REQUIREMENTS

MODULARITY
- REFERENCE CELL CHARACTERISTICS
- CIRCUITS PER MODULE

SAFETY
- 30 Vdc OPEN CIRCUIT VOLTAGE AT -20°C

RELIABILITY
- HOT SPOT HEATING

ARRAY ALIGNMENT

MAJOR ISSUES INCLUDE:
- ARRAY LOCATION ON ROOF WITH RESPECT TO ROOF PENETRATION
- ROOF SIZE
- RIDGE TO EAVE DISTANCE
- ESTABLISHMENT OF ANY NECESSARY DATUM
- CUMULATIVE PLACEMENT ERROR
- TOLERANCES

METHODS:
- BLOCK/BRACKET
- STRIP/CHANNEL
- GRID/MESH

ARRAY ATTACHMENT

MAJOR CONCERNS INCLUDE:
- LOCATION OF WEATHERABLE SURFACE (i.e., either standard roof surface or module surface)
- SUPPORT CONDITIONS
- LOADING CONDITIONS
- RELIABILITY OF FASTENING METHODS

METHODS:
- MECHANICAL FASTENERS
- PRESSURE FITTING GASKETS
- ADHESIVES

ARRAY CONNECTION

MAJOR CONCERNS INCLUDE:
- CONNECTOR PROFILE AND LOCATION (i.e., dry or wet) OF CONNECTOR
- CONNECTOR REUSE AND ACCESSIBILITY
- SAFETY PROTECTION FROM EXPOSED CONDUCTIVE PARTS

METHODS:
- JUNCTION BOXES
- QUICK CONNECT/DISCONNECT
- QUICK PERMANENT CONNECT

ARRAY CABLING

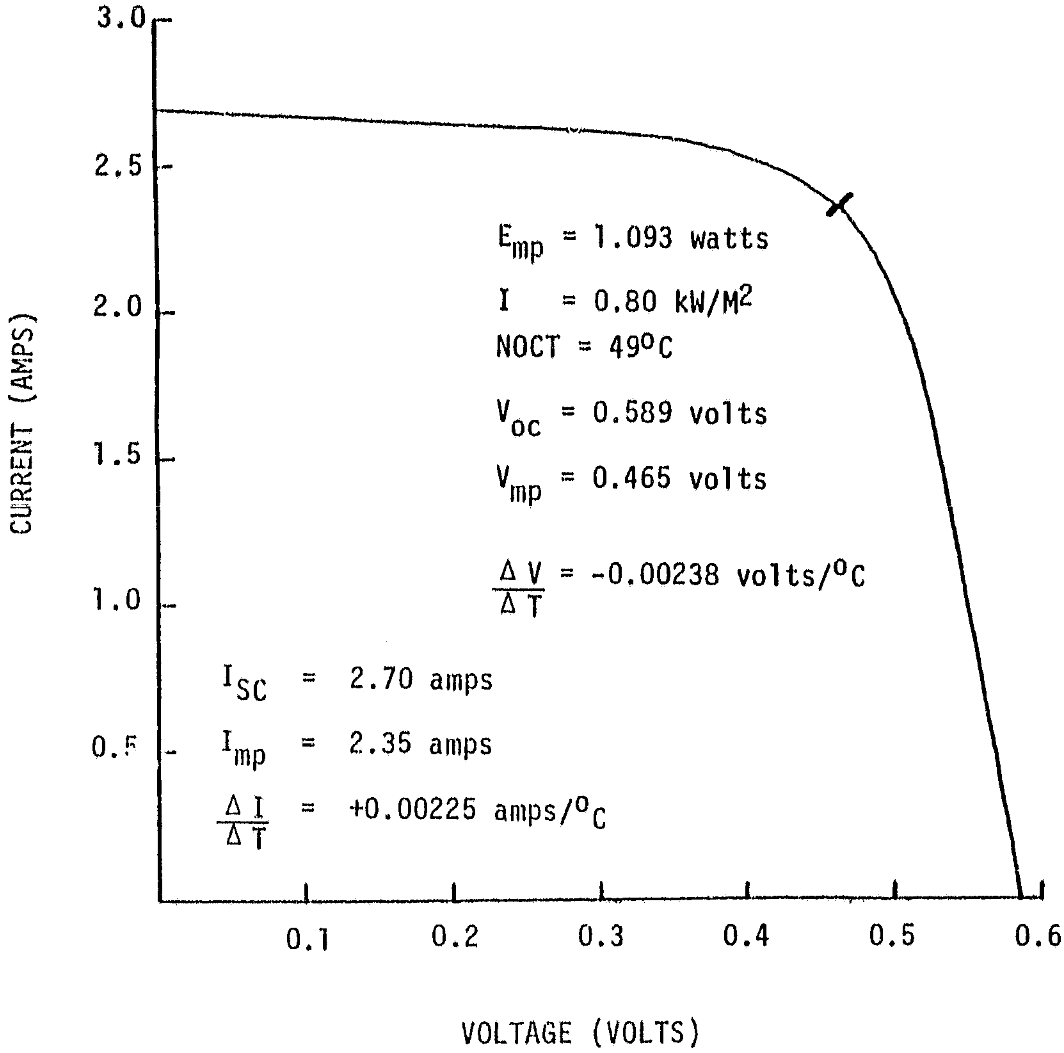
MAJOR ISSUES INCLUDE:
- APPROVAL AND QUALIFICATION
- FACTORY VS. FIELD REQUIREMENTS
- SAFETY PROTECTION FROM EXPOSED CONDUCTIVE PARTS

METHODS:
- SPLICE
- RIBBON
- MAT

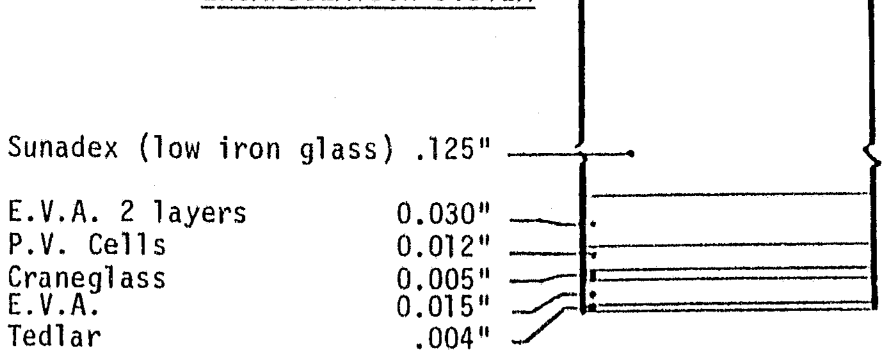
Reference Cell and Encapsulation System

REFERENCE CELL I-V CHARACTERISTICS

10 CM x 10 CM SEMICRYSTALLINE SILICONE



ENCAPSULATION SYSTEM



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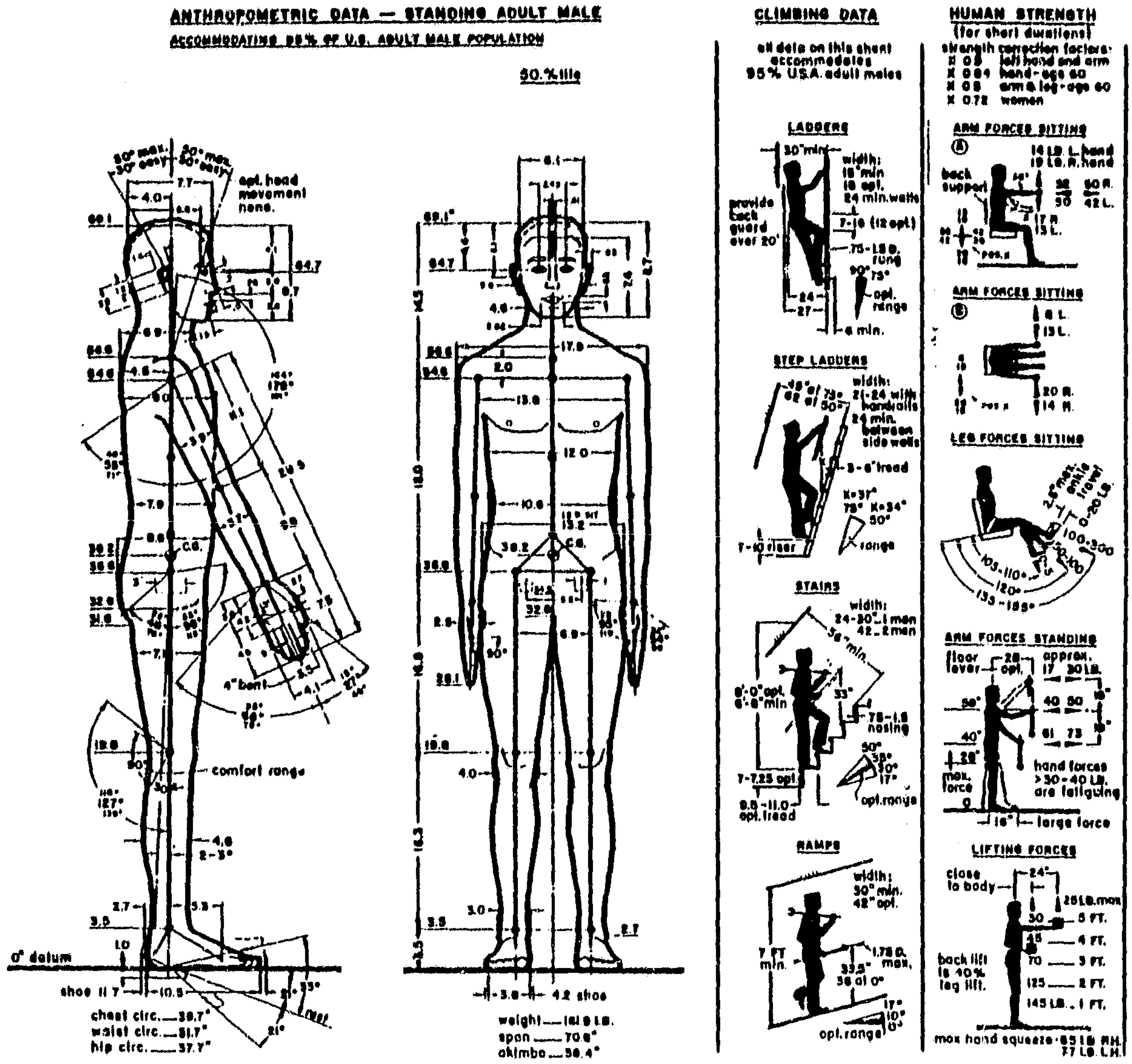
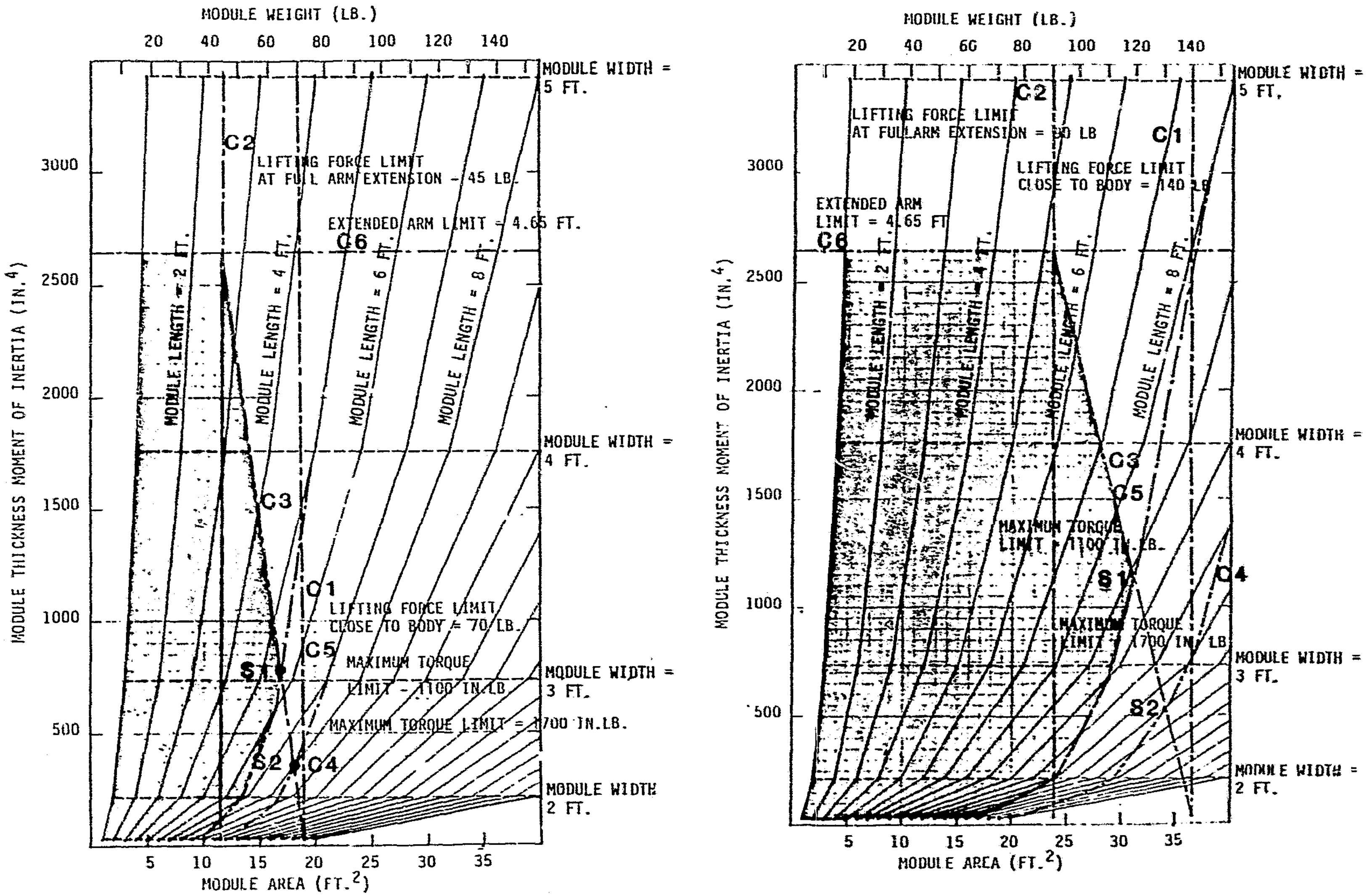
Anthropometric Data



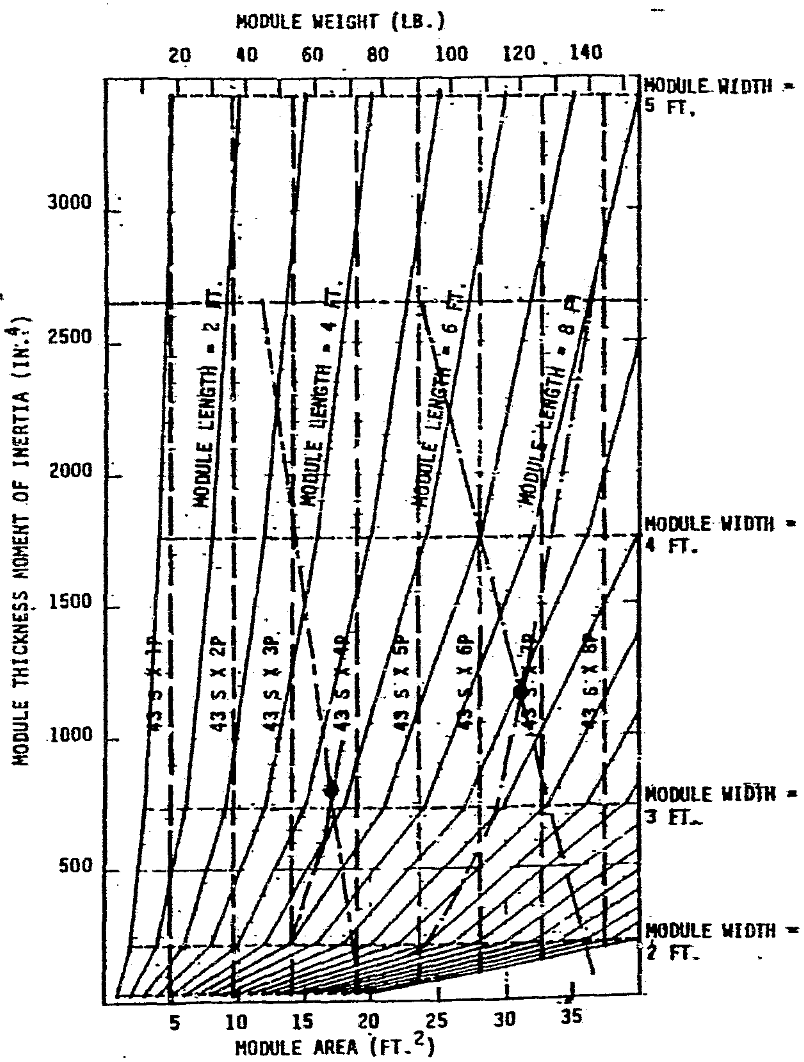
Module Handling Limits



Model Code Load Components

MODEL CODE	TOTAL LOAD COMPONENTS						
	DEAD LOAD	LIVE LOAD	WIND LOAD	EARTHQUAKE LOAD	THERMAL LOAD	IMPACT LOAD	SNOW LOAD
BOCA	15 lb/ft^2	20 lb/ft^2	36 lb/ft^2	N/A ANSI A 58.1	Not Specified	Covered by other loads	5 lb-70 lb* (SE) (NE) 0.8 = S
ICBO	15 lb/ft^2	20 lb/ft^2 (incl. snow)	50 lb/ft^2	N/A Same as Above	Not Specified	Covered by other loads	$R_s = \frac{S}{40} - \frac{1}{2}$ for each degree over 20^0 pitch S= snow $load/ft^2$ R_s= reduction factor
SBCC	15 lb/ft^2	20 lb/ft^2	47 lb/ft^2	N/A Same as Above	Not Specified	Covered by other loads	

Handling and V_{OC} Conditions



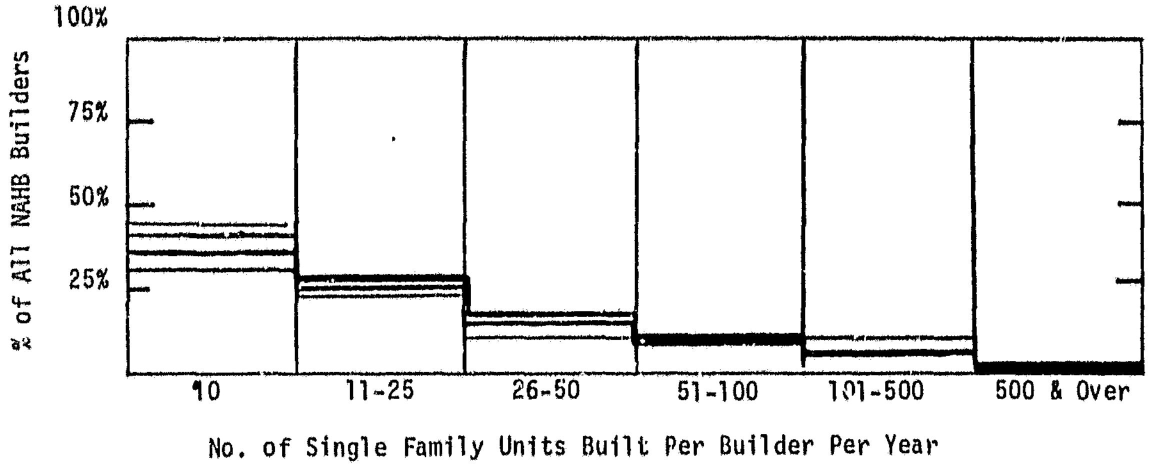
MODULE CIRCUIT		AREA		WEIGHT
CONFIGURATION	OUTPUT (W_{mp})	M^2	FT^2	(LB)
43S x 1P	46.99	.43	4.63	17.95
43S x 2P	93.98	.86	9.25	35.90
43S x 3P	140.96	1.29	13.88	53.86
43S x 4P	187.95	1.72	18.51	71.81
43S x 5P	234.94	2.15	23.13	89.76
43S x 6P	281.93	2.58	27.76	107.71
43S x 7P	328.92	3.01	32.39	125.66
43S x 8P	375.91	3.44	37.01	143.62

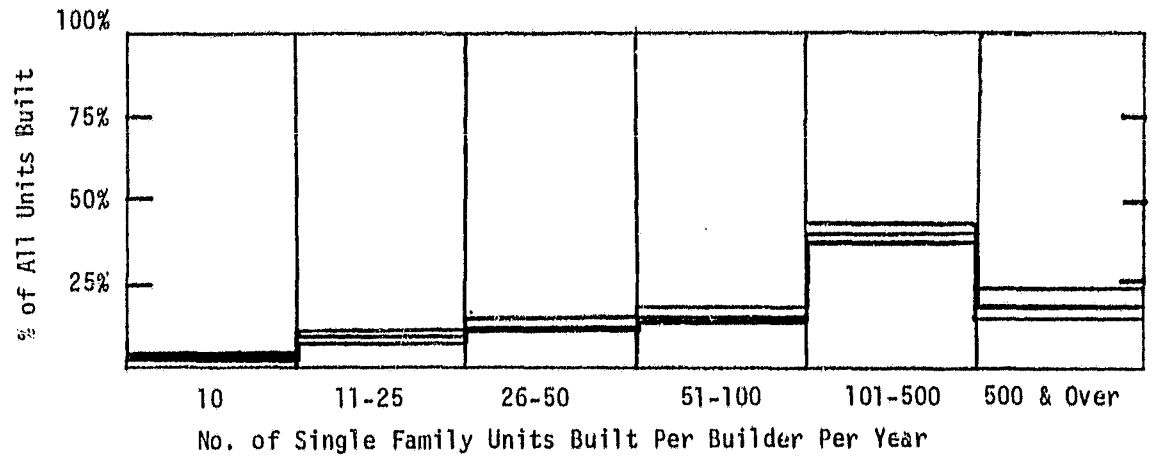
- V_{oc} < 30 vdc at -20°C
- Maximum series string = 43 cells
- 10 cm x 10 cm cells

Estimates of Field Application

ELEMENT	ANNUAL PRODUCTION (M^2)		
	10000	50000	500000
Cells (@ 0.01 M^2)	1,000,000	5,000,000	50,000,000
Peak Power Output (MWp)	1.229	6.143	61.431
Max Power Output (MWp)	0.921	4.605	46.050
Houses at Nom. 4 KWp	193	965	9650
Houses at Nom. 8 KWp	96	482	4825

Estimates of Field Installation





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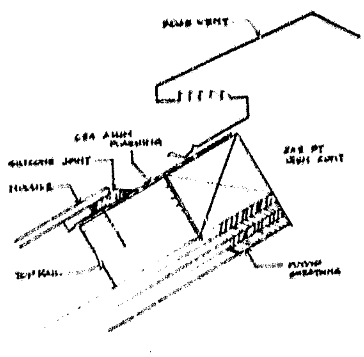
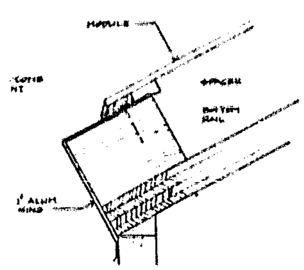
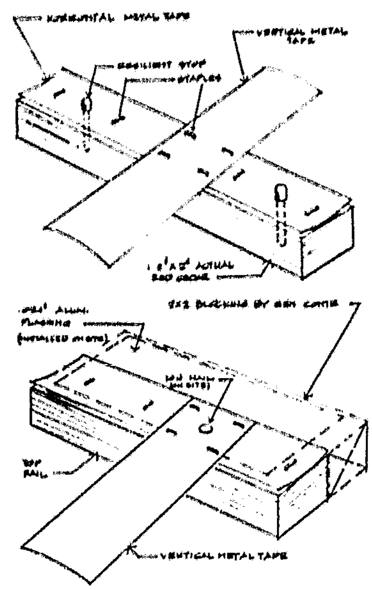
Design Concept Optimization

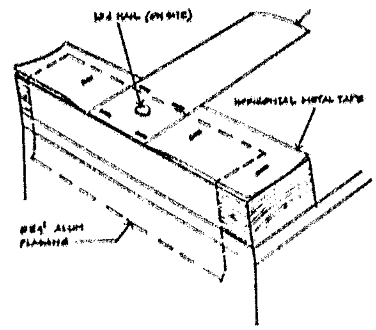


FLASHING AT BOTTOM RAIL (EAVE)

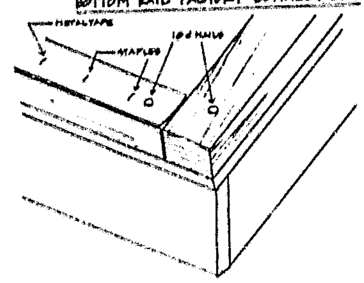




TYPICAL VERTICAL METAL TAPE/ TOP RAIL FACTORY CONNECTION



TYPICAL VERTICAL TAPE/ BOTTOM RAIL FACTORY CONNECTION



TYPICAL SIDE RAIL-TO-BOTTOM RAIL CONNECTION BEFORE FLASHING

5 KW PV ARRAY INSTALLATION MAN-HOURS

TASK	GLAZIER	GLAZIER	LABORER	LABORER	TOTAL
COORDINATION & SET-UP	1/4	1/4	3/4	3/4	2
ROOF CHECK	1/4	1/4			1/2
SET #1 SIDE RAIL	1/4	1/4			1/2
PREPARE MODULES & FRAME			1/4	1/4	1/2
HOIST #1 BUNDLE & ROLL OUT	1/4	1/4	1/4	1/4	1
SQUARE, TACK, SHIM, NAIL	1/2	1/2	1/4	1/4	1-1/2
SET #2 SIDE RAIL	1/4	1/4			1/2
PREPARE #2 BUNDLE			1/4	1/4	1/2
HOIST #2 BUNDLE & ROLL OUT	1/4	1/4	1/4	1/4	1
SQUARE, TACK, SHIM, NAIL	1/4	1/4	1/4	1/4	1
PREPARE FLASHING			1/2	1/2	1
INSTALL FLASHING	1/2	1/2			1
SUBTOTAL	2-3/4	2-3/4	2-3/4	2-3/4	11
INSTALL 1ST ROW	3/4	3/4	3/4	3/4	3
BREAK FOR LUNCH	1/2	1/2	1/2	1/2	2
INSTALL 2ND ROW	1/2	1/2	1/2	1/2	3
INSTALL 3RD ROW	1/2	1/2	1/2	1/2	2
INSTALL 4TH ROW	1/2	1/2	1/2	1/2	2
INSTALL 5TH ROW	1/2	1/2	1/2	1/2	2
INSTALL 6TH ROW	1/2	1/2	1/2	1/2	2
INSTALL 7TH ROW	1/2	1/2	1/2	1/4	1-3/4
INSTALL 8TH ROW	1	1	3/4		2-3/4
CLEAN UP			1/4	1-1/4	1-1/2
SUBTOTAL	4-3/4	4-3/4	4-3/4	4-3/4	19
TOTAL	8	8	8	8	32

PRICING SHEET For Scheme No. BHKRA-3

Cost Component: COST PER REPLACEMENT ACTION

Date: April 29, 1981
Array Designer: Burt Hill Kosar Rittelmann Associates

COST/CREDIT ITEM	QUANTITY	MAT'L UNIT COST	MAT'L COST	LABOR UNIT COST	LABOR COST	TOTAL INSTALLED COST	REMARKS
Set-Up	0.75 Hrs.			$19.92	$14.94	$14.94	
Cut Out Module	0.25 Hrs.			10.99	2.75	2.75	
Remove Module	0.25 Hrs.			19.92	4.98	4.98	
Prepare Module	0.25 Hrs.			8.93	2.23	2.23	
Place Module	0.25 Hrs.			19.92	4.98	4.98	
Sealant	1 Tube	$7.00	$7.00	10.99	2.00	9.00	
Clean-Up	0.33 Hrs.			19.92	6.64	6.64	
TOTAL						$45.52	
TOTAL COST/M^2						$52.93	Per Square Meter of Module

PRICING SHEET For Scheme No. BHKRA-3

Cost Component: MINOR UPKEEP COSTS

Date: April 29, 1981
Array Designer: Burt Hill Kosar Rittelmann Associates

COST/CREDIT ITEM	QUANTITY	MAT'L UNIT COST	MAT'L COST	LABOR UNIT COST	LABOR COST	TOTAL INSTALLED COST	REMARKS
Cleaning	1					$75.00	
TOTAL						$75.00	
TOTAL COST/M^2						$ 1.36	

Life-Cycle Cost Calculation

$$R_L = \frac{C_M + C_{MD} + C_{MLC}}{\eta_M * \eta_B * S * H * \varepsilon_{LC}} + \frac{C_{BLC}}{H * \varepsilon_{LC}}$$

R_L = Total system life-cycle energy cost (\$/kWh)

C_M = Initial module cost per unit area of module (\$/M^2)

C_{MD} = Balance of module-dependent system initial cost per unit of module (\$/M^2)

C_{MLC} = Module-dependent life cycle cost exclusive of initial cost, per unit of module (\$/M^2)

C_{BLC} = Total module-independent balance-of-plant life-cycle cost per kilowatt of total plant output power at insolation S and NOCT (\$/kWp)

η_M = Module efficiency (power output per unit of total module area at insolation S and NOCT, divided by S)

η_B = Balance of plant efficiency (average plant power output divided by array power input)

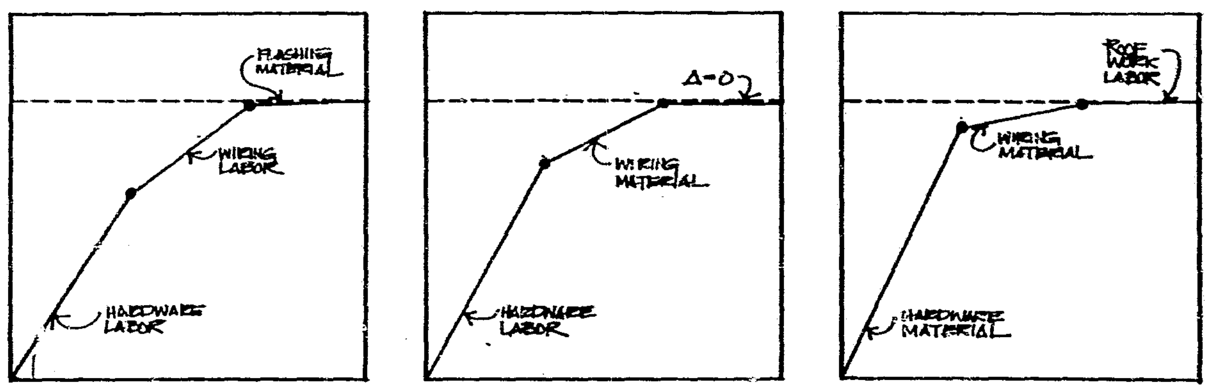
S = Reference insolation level (kW/M^2)

H = Peak insolation hours per year captured by the array (Langleys/day divided by S, mW/cm^2 * 423.4 hrs/yr)

ε_{LC} = Life cycle summation of annual fraction of initial energy output

Initial Cost Drivers

	Integral	Direct	Standoff
Array Installation Total	$0.20	$0.17	$0.13
• Sealants Materials and Labor • Flashing Materials and Labor • Mounting Hardware/Glazing Gaskets Materials • Field and Shop Assembly Labor			
Roof Work	$0.03	0	0
Wiring Total	$0.04	$0.04	$0.04
• Harnesses • Connectors • Busbars			
Modules	$0.93	$0.93	$0.93
Standard Roof Credit	$0.10	$0.04	0
Net Installed Cost	$1.10	$1.10	$1.10



Program Optimization Status

Module Production
- module geometry
- circuit design
- production rates

Hardware Fabrication
- mounting attachment
- connectors
- pre-wiring
- production rates

Shipping, Handling and Distribution
- modules
- hardware
- end-use economies-of-scale

Installation and Specification
- system size
- module size
- builder profiles

Operation and Maintenance
- startup/shutdown
- minor upkeep
- diagnostics
- replacement

ARRAY SAFETY DESIGN

UNDERWRITERS LABORATORIES INC.

A. Levins

I DRAFT STANDARD FOR FLAT-PLATE PHOTOVOLTAIC MODULES AND PANELS

II SAFETY SYSTEMS FOR PHOTOVOLTAIC ARRAYS

III COMPONENTS FOR USE IN IMPLEMENTING SAFETY SYSTEMS

Standard for Safety: Flat-Plate PV Modules and Panels

EFFORT TO DEVELOP STANDARD WAS INITIATED BY AND IN LARGE PART SPONSORED BY THE JET PROPULSION LABORATORY (JPL) AS A PART OF THE LSA PROJECT.

STANDARD IS BEING WRITTEN IN RECOGNITION OF PROPOSED NATIONAL ELECTRICAL CODE (NEC) ARTICLE ON PHOTOVOLTAICS AND THE SEVERAL PROPOSED SAFETY SYSTEMS, SO THAT MODULES AND PANELS WILL BE CAPABLE OF BEING INSTALLED IN CONFORMANCE WITH PROVISIONS OF THE NEC.

STANDARD RELATES TO FACTORY BUILT ITEMS, CODES (E.G.-NEC) RELATE TO INSTALLATION.

FIRST DRAFT OF THE STANDARD WAS PRESENTED AND USED AS A BASIS OF DISCUSSION AT SAFETY WORKSHOP HELD AT JPL, FEBRUARY 1981.

STANDARD IS INTENDED TO ADDRESS SAFETY ISSUES ONLY AS MAY ARISE FROM THE GENERATION AND USE OF ELECTRICITY AND DOES NOT ATTEMPT TO ACHIEVE ANY "STANDARDIZATION" OF PRODUCTS, EXCEPT WHERE SUCH MAY BE NECESSARY FOR SAFETY.

STANDARD IS NOW AT A STAGE WHERE TRIAL EVALUATIONS TO IT ARE DESIRABLE, TO DETERMINE ITS WORKABILITY.

STANDARD IS DIVIDED IN TWO MAJOR PARTS:

A) CONSTRUCTION
B) PERFORMANCE

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Safety Systems

GROUND FAULT SYSTEMS FOR PROTECTION AGAINST HAZARDS FROM SHOCK, MAY SERVE AS PART OF A MECHANISM AS AN ALTERNATIVE TO RESTRICTIONS ON MAXIMUM VOLTAGE, VOLTAGE LIMIT (300 OR 600 VOLTS) BEING PROPOSED BY NATIONAL ELECTRICAL CODE AD-HOC COMMITTEE.

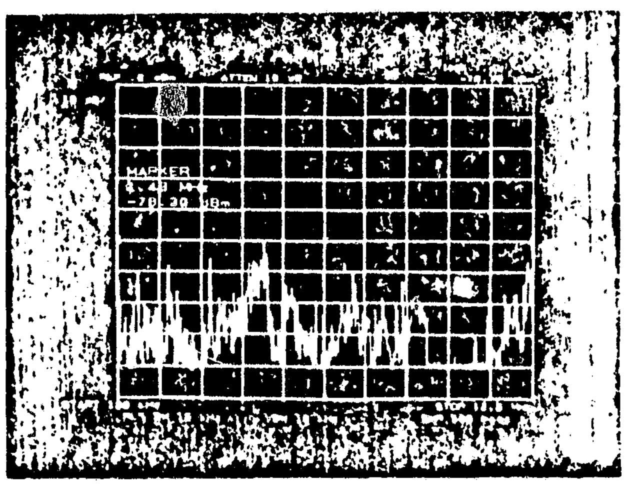
AS GROUND FAULT SYSTEM WILL NOT PROTECT AGAINST HAZARDS ARISING FROM LINE-TO-LINE CONTACT, PARTS OF THE ARRAY WHICH ARE MORE THAN A SPECIFIED VOLTAGE WITH RESPECT TO EACH OTHER SHOULD BE SPACED MORE THAN TWO ARMS LENGTHS APART.

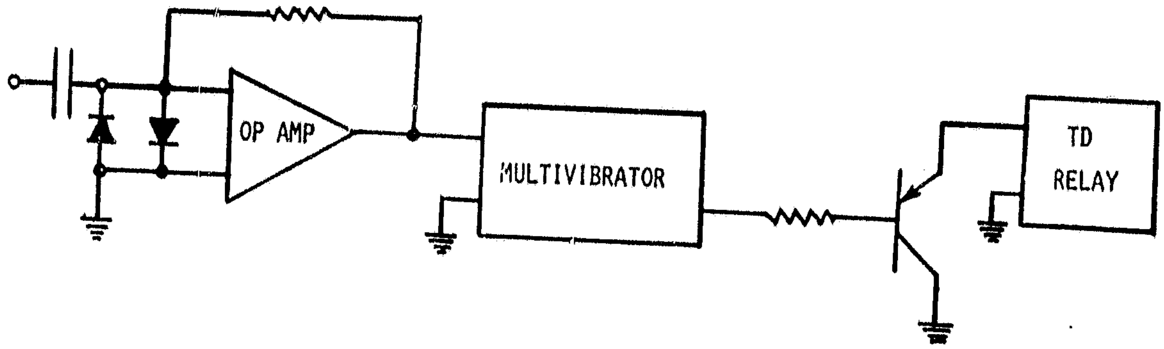
GROUND FAULT SYSTEM TO PROTECT AGAINST SHOCK HAZARD SITUATIONS WILL ALSO PROVIDE PROTECTION AGAINST ARCING TO GROUND (FIRE) HAZARD SITUATIONS.

GROUNDING - NEC AD-HOC COMMITTEE HAS ACCEPTED CONCEPT OF ALTERNATE MEANS TO ACHIEVE VIRTUES OTHERWISE ASSOCIATED WITH "SOLID GROUNDING". IF THE SECTION THAT IS INCORPORATED IN THE NEC REFLECTS THIS, GROUND FAULT SYSTEMS ARE A STEP CLOSER TO REALITY.

In-Circuit Arc Detection

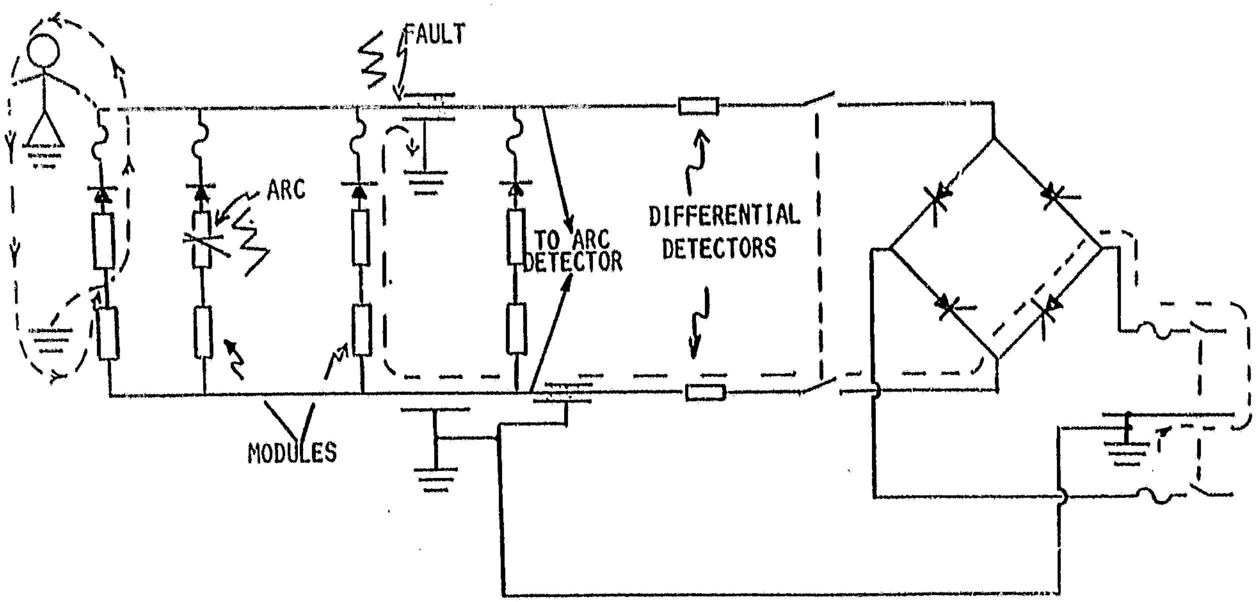
- PROBLEM -- IN-CIRCUIT ARCING CAN RESULT IN MATERIAL IGNITION AND IS DIFFICULT TO DETECT BECAUSE CURRENT APPEARS NORMAL.
  - MAGNITUDE
  - FLOW PATH
- APPROACH -- INVESTIGATE ARC CHARACTERISTICS
  - MATERIAL
  - FREQUENCY
  - BANDWIDTH
  - ENERGY LEVEL
- EXPERIMENTAL RESULTS
  - 8 APRIL 1981
  - FREQ. SPECT. 110 KHZ TO 12 MHZ
  - ARCING MODE: OPEN CIRCUITED CELL INTERCONNECTS (1 OF 15 IN PARALLEL)
  - V_{DC} = 147 V
  - P_{LOAD} = 4 KW





- HIGH FREQUENCY RESPONSE DEVICE: OUTPUT OPEN CIRCUITS ARRAY, THUS TERMINATING ARC.
- PRESENT STATUS-CONCEPT APPEARS FEASIBLE
  - LOCATION DEPENDENT
  - SUSCEPTIBLE TO POWER CONDITIONER INTERFERENCE
- FUTURE PLANS
  - DEVELOP INCREASED SENSITIVITY AND DISCRIMINATION
  - IN SITU TESTING

Grounding and Ground-Fault Systems



GROUND FAULT SYSTEMS MAY OPERATE IN EITHER OF TWO WAYS:

A) DIFFERENTIAL
B) DETECTING CURRENT IN GROUND PATH

	PROS	CONS
DIFFERENTIAL	A) FUNCTION WHERE BASIC GROUND IS NOT UNDER USERS CONTROL	A) COSTS AND DIFFICULTY OF DETECTING SMALL IMBALANCE IN LARGE OVERALL CURRENT
	B) CAN DETECT SPURIOUS GNDS	B) POWER LOSS IN DETECTORS
	C) CAN FUNCTION ON A SEGMENT OF CIRCUIT	
CURRENT IN GND PATH	A) ONLY ONE CURRENT IS MEASURED, CIRCUIT IS SIMPLE	A) NO GROUNDS PERMITTED OTHER THAN THROUGH DETECTOR
		B) CIRCUIT CANNOT BE SEGMENTED

FRAME GROUNDING SHOULD KEEP FRAME AT POTENTIAL OF EARTH AROUND ARRAY. THIS MAY NECESSITATE MULTIPLE GROUNDS DEPENDING UPON SOIL RESTIVITY. WHEN ARRAY CIRCUIT IS GROUNDED AT CONDITIONER, AND NO METAL CONDUCTOR (WIRE) IS RUN BETWEEN GROUND RODS OF FRAME (AT ARRAY) AND CIRCUIT (AT CONDITIONER), EARTH BETWEEN THE TWO IS AN ELECTROLYTE FOR LEAKAGE CURRENT PATH. ONE OF THE ELECTRODES MAY BE CONSUMED AS A RESULT OF ELECTROLYTIC ACTION. THEREFORE, A WIRE BETWEEN GROUND RODS IS SUGGESTED.

ARC DETECTOR - TO DETECT IN-CIRCUIT ARCS.

ARRAY DYNAMIC WIND LOADING

BOEING ENGINEERING & CONSTRUCTION

Wind Loads on Flat-Plate PV Array Fields

Objective:

- Develop more refined estimates of wind loading on flat-plate photovoltaic modules and array support structures and develop design guidelines

Approach:

- Theoretical (Phase II - Report No. DOE/JPL954833-79/2)
  - Literature search
  - Separated flow analysis
- Experiment (Wind Tunnel Test - Phase III - Report No. DOE/JPL954833-81/3)
  - Colorado State University environmental tunnel
  - 1/24 scale model
- Dynamic Analysis (Phase IV)
  - Combined theoretical - experimental analysis

Wind Tunnel Test

Steady State Test

- Measured Steady State Pressure Coefficients (Report No. DOE/JPL954833-81/3
- Calculated RMS Pressure Coefficients of Fluctuating Pressures

Non-Steady State Test

- Recorded Array Upper and Lower Pressures Simultaneously
- Calculated Auto and Cross Spectrums

Dynamic Analysis

Approach:

- Theoretical Structural Dynamic Model
- Utilizes Auto and Cross Spectrums
- Utilizes Random Harmonic Analysis Techniques

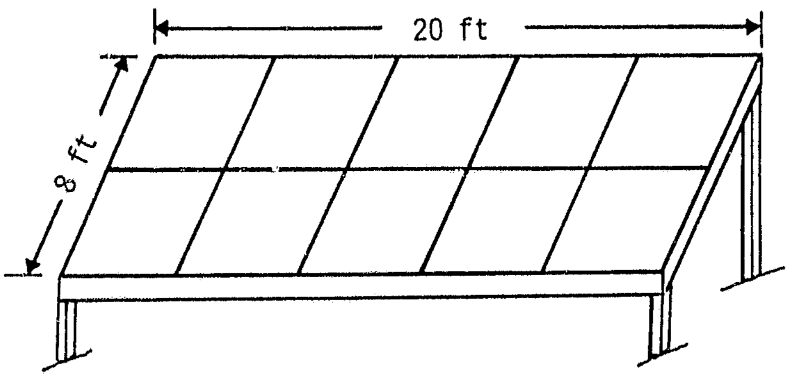
Results

- RMS Dynamic Loads
  - Dependent upon structural characteristics and configuration

- Magnification Factor

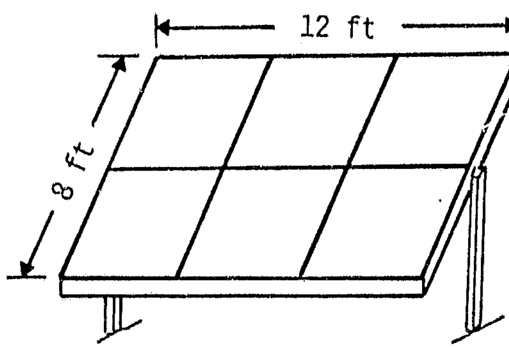
  Theoretical RMS Dynamic Loads/
  Experimental RMS Pressure Loads

Array Characteristics



Wt.= 977#
1^{st} Plate
Bldg. Mode = 10 Hz

Configuration I

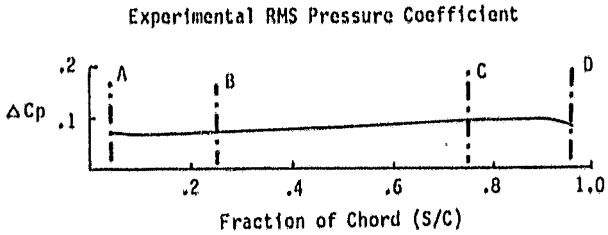


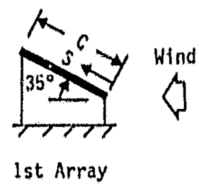
Wt.= 933#
Pitch Mode = 3 Hz
1^{st} Plate Bldg. Mode = 10 Hz

Configuration II

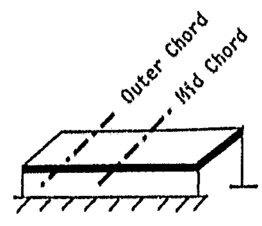
Dynamic Analysis Results

Configuration I - Fence - 1st Array



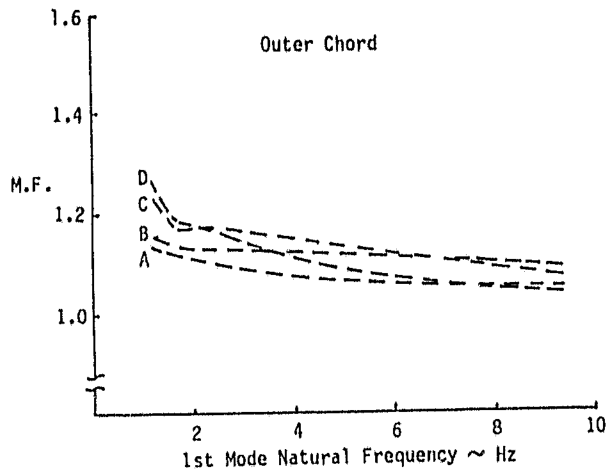


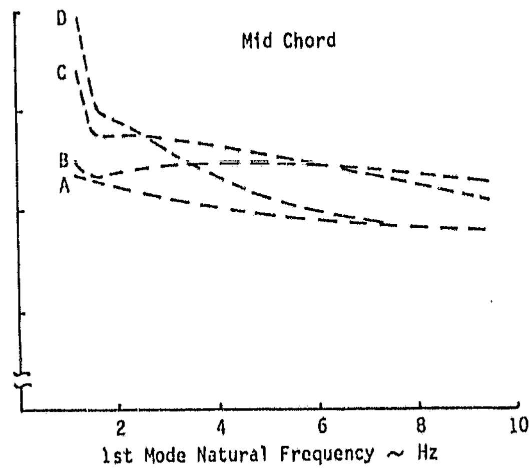
1st Array
(Fence)



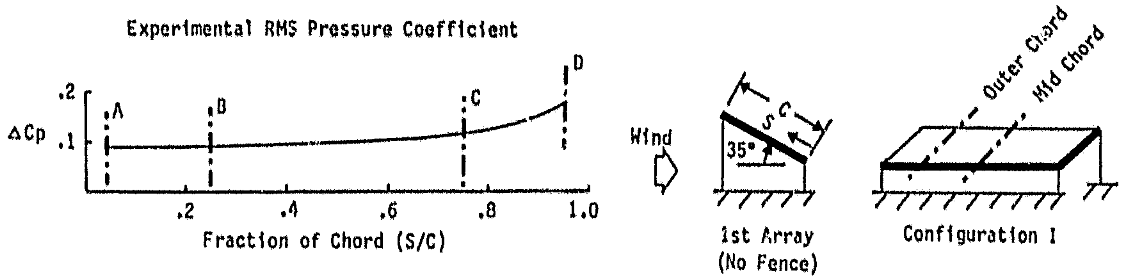
Configuration I

$$\text{Magnification Factor (M.F.)} = \frac{\text{Theoretical RMS Dynamic Load}}{\text{Experimental RMS Pressure Load}}$$

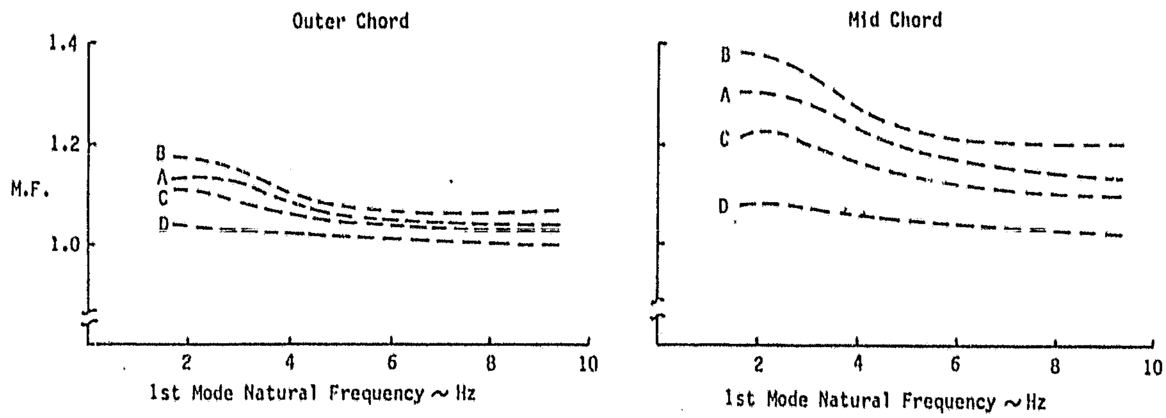




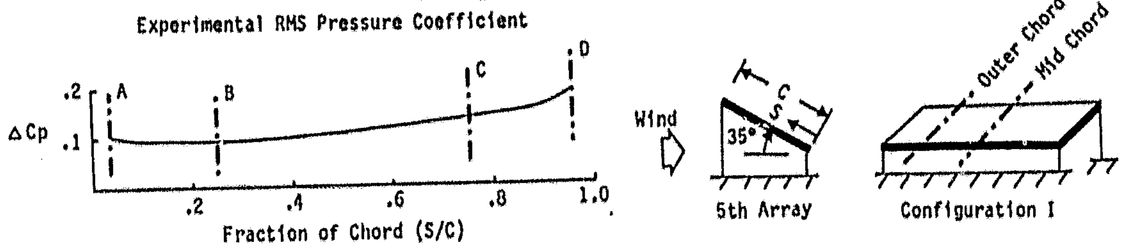
Configuration I - No Fence - 1st Array



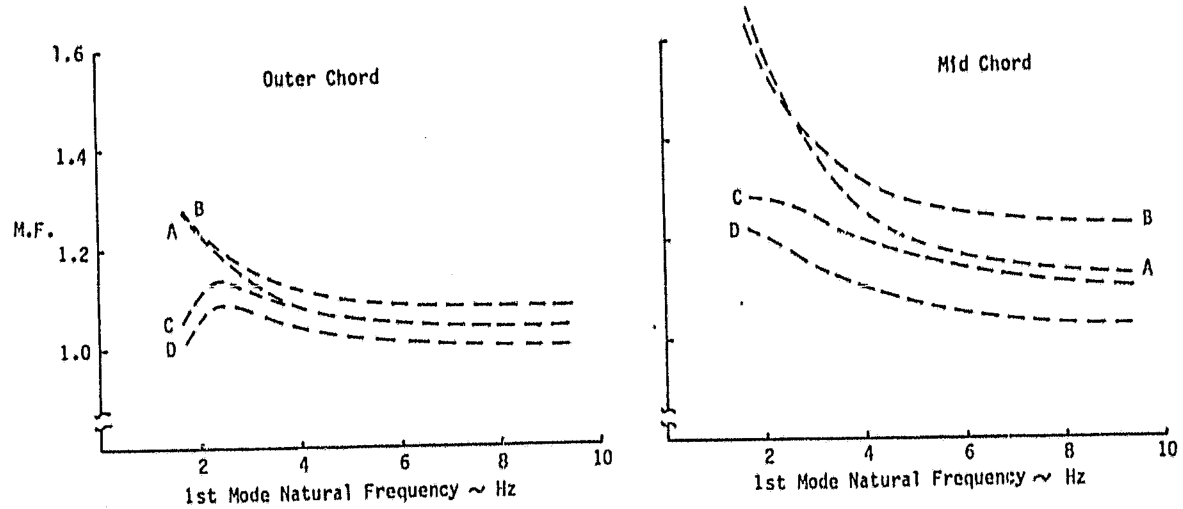
$$\text{Magnification Factor (M.F.)} = \frac{\text{Theoretical RMS Dynamic Load}}{\text{Experimental RMS Pressure Load}}$$



Configuration I - 5th Array



$$\text{Magnification Factor (M.F.)} = \frac{\text{Theoretical RMS Dynamic Load}}{\text{Experimental RMS Pressure Load}}$$

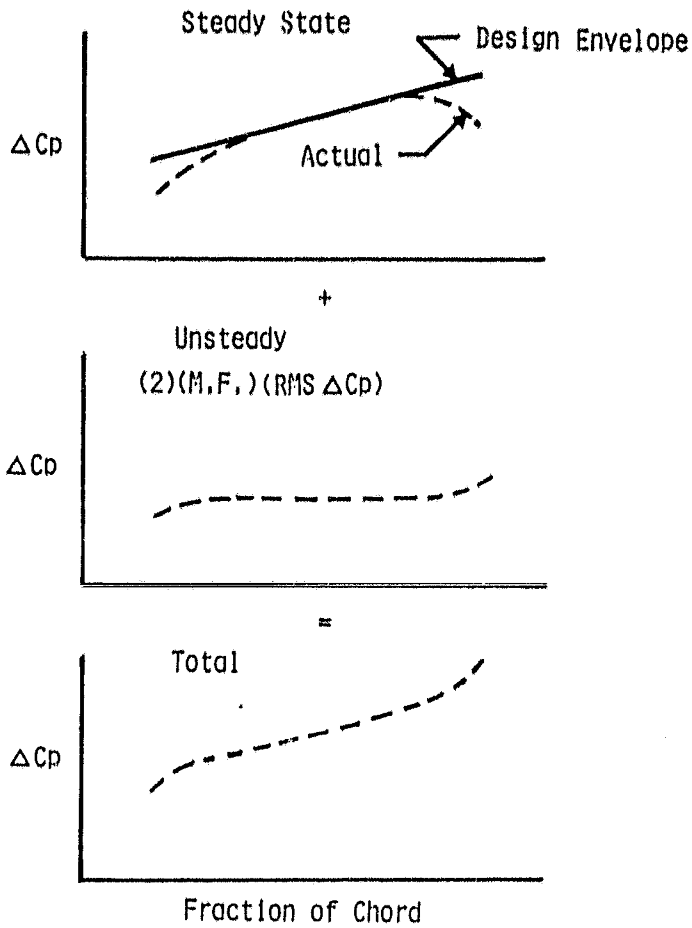


Application to Design

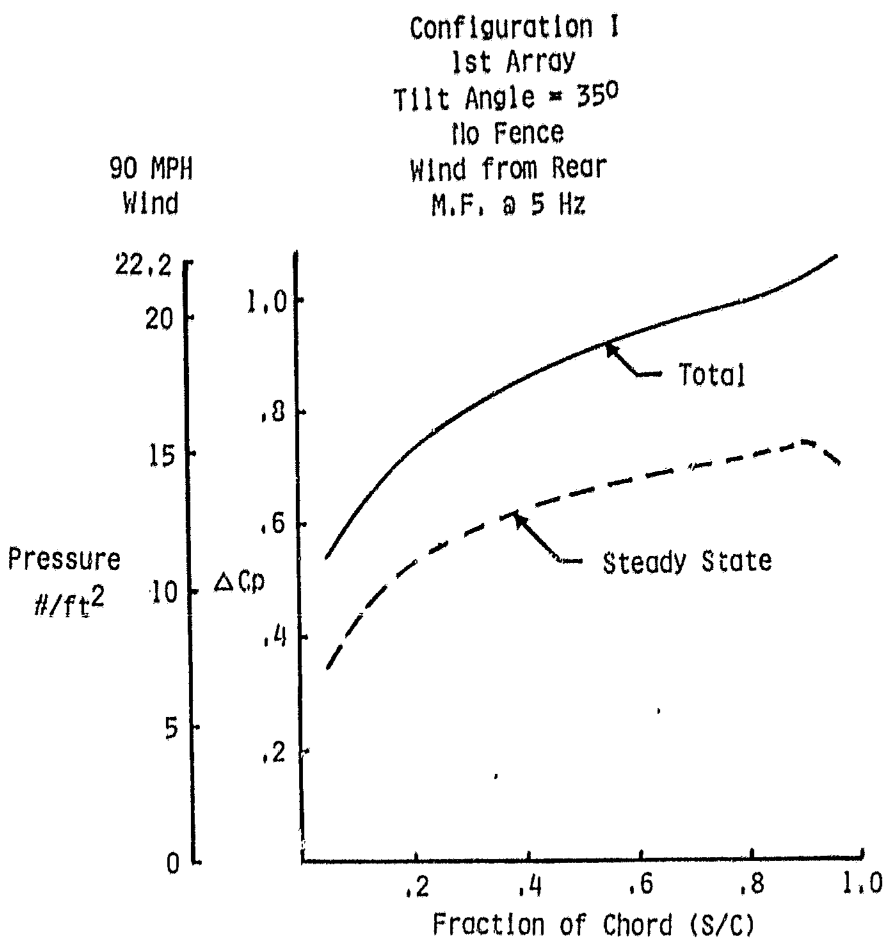
- Steady State
  Pressure Coefficient
  (Report No. DOE/JPL954833-81/3)

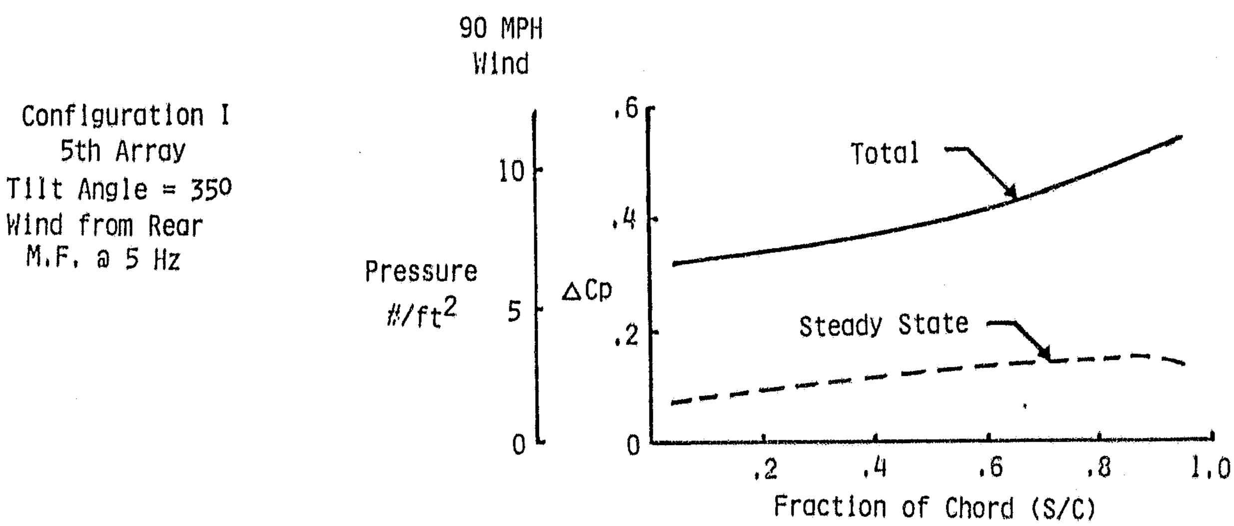
- Unsteady Pressure Coefficient
  - RMS pressure coefficient times 2 (95.5% probability)
  - Magnification factor

- Design Pressure Coefficient

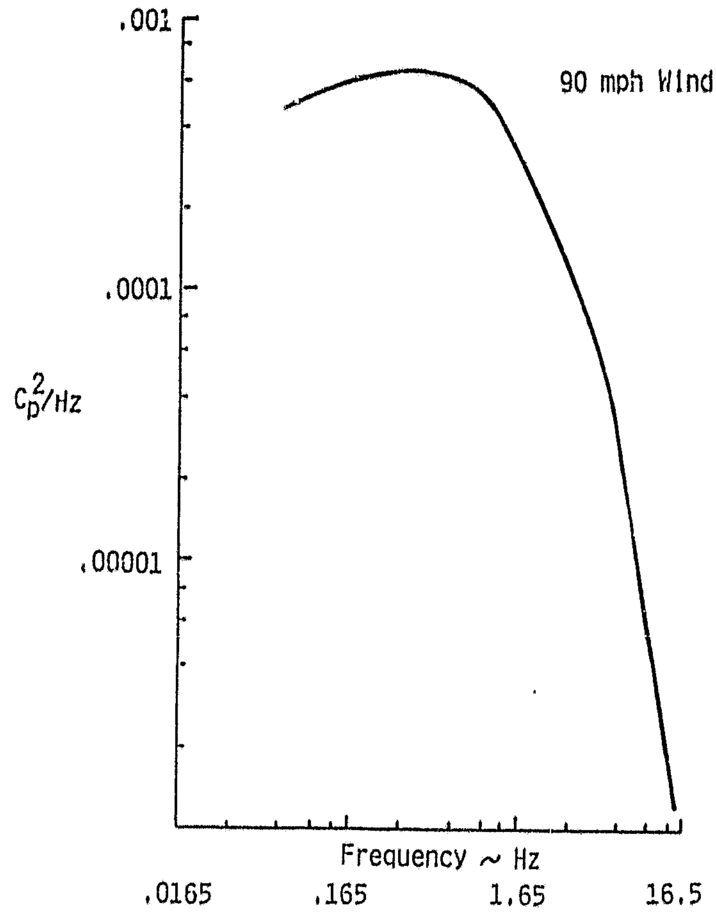


Design Wind Loads





Typical Auto and Cross Spectra



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PROJECT ANALYSIS AND INTEGRATION AREA

P. K. Henry, Chairman

SAMICS

A discussion of planned improvements in the SAMICS methodology was presented in response to a number of comments and criticisms made by participants in the SAMICS Critique at the 17th PIM.

Environmental Control Costs

The SAMICS Cost Account Catalog and the indirect charge matrix in SAMIS are being updated to include more recent and detailed environmental and effluent-control equipment and processing costs. The various effluents will create indirect requirements based on the type of effluent and the volume as specified on Format A. These improvements will be incorporated in SAMIS Release 4.

Energy Payback of Flat-Plate PV Modules and Arrays

An analysis of energy payback times was offered in response to several recent articles in popular and technical literature claiming that PV was subject to a 15-to-20 year energy payback time. The articles were based on obsolete or incorrect data. The present analysis incorporates the most recent energy content information accumulated over the past year by the PA&I Area.

The presentation in the PA&I technical session compared 1976 space modules, which had an energy payback time in terrestrial use of 11 to 21 years, with terrestrial modules in 1976 (6 to 11 years payback), 1982-83 modules (3 to 5.4 years payback) and 1986-90 ribbon-based technology (0.6 to 1.1 years payback). The balance of the systems add 0.8 to 1.5 years to the system energy payback time, for a total of 1.4 to 2.6 years.

This analysis will soon be published in a journal article.

Spinoff Benefits of the DOE PV Program

The PV program has conducted advanced research and technology development since 1976. Several unexpected technology spinoffs have developed in that time, and in some cases substantial economic benefits can be quantified. Continued R&D may produce further spinoffs of considerable value.

Consideration is given to the progress resulting from the DOE Program and to progress that was likely to have occurred within private industry in the absence of a federal program. The major reasons for net program benefits are:

(1) PV R&D has occurred in high-risk areas. For example, more than 80% of the silicon purification concepts studies have failed. This has discouraged innovations in that area for more than 20 years.

(2) R&D payback from spinoffs is very slow in several cases. For example, new techniques for sawing crystal ingots will require five to 10 years of development to catch up with and surpass conventional processes. The firms that are leading the way in this area are small companies that could not have sustained large negative cash flows over such a period.

(2) Many spinoffs will benefit the semiconductor industry and its customers. Semiconductor firms concentrate R&D funds on their big cost drivers, such as quality of product, miniaturization of devices, and improving process yields. PV program R&D has emphasized reduction of material costs and key process step costs that complement rather than duplicate semiconductor R&D. Small reductions in semiconductor materials costs do not attract many semiconductor firms' R&D dollars, but are of significant value to the industry as a whole.

Two spinoffs that have quantifiable benefits are low-cost semiconductor-grade silicon and more efficient crystal ingot pullers. The program originally sought solar-grade silicon and ingots; semiconductor quality is a windfall. For purposes of this analysis, it is assumed that in the absence of the program, silicon costs would have fallen according to historical trends and that the price will drop suddenly in 1991 to the low cost available from the program's technology. Also, it is assumed that in the absence of the program, the value added to that silicon by ingot growth also will fall at about a 75% learning-curve rate, consistent with historical trends, and that prices would have dropped to the levels avaiable from the new PV program technology in 1987.

Using a real discount rate of 10%, the net present value of these benefits is $984 million in 1980 dollars.

RESPONSE TO SAMICS CRITIQUE AT 17th PIM

JET PROPULSION LABORATORY

P. K. Henry

COMMENT/CRITICISM

- "SAMIS REPORTS DO NOT CONTAIN INFORMATION USEFUL TO CORPORATE FINANCIAL ANALYSTS AND PLANNERS"

ANALYSIS

- RIGHT!

ACTION

- SAMIS RELEASE 4 (OCT 1981) WILL HAVE YEAR-BY-YEAR FINANCIAL REPORTS: INCOME STATEMENT, BALANCE SHEET, SOURCE, AND APPLICATION OF FUNDS

COMMENT/CRITICISM

- "SAMIS COSTS TOO MUCH TO RUN AND IS HARD TO USE"

ANALYSIS

- MANY RUNS REQUIRED BY SOME USERS DUE TO IMPROPER OR ERRONEOUS INPUT DATA
- USERS UNFAMILIAR WITH COST SAVING OPTIONS
- USERS GUIDE DIFFICULT FOR UNINITIATED TO USE

ACTION

- SAMICS SHORT COURSE WILL BE OFFERED, POSSIBLY WITH NEXT PIM
- ENGINEER'S USERS GUIDE TO SAMIS BEING WRITTEN FOR NEXT SAMIS RELEASE IN OCTOBER 1981
- USER'S QUICK REFERENCE CARD BEING WRITTEN
- REVISED FORMAT A AND C FORMS WITH MORE EXPLICIT INSTRUCTIONS AND FORMAT A DATA DERIVATION SHEET

PROJECT ANALYSIS AND INTEGRATION AREA

COMMENT/CRITICISM

- "ARE SAMICS RESULTS BELIEVABLE?"

ANALYSIS

- VALIDATION ACTIVITIES AND EXPERIENCE WERE NOT VISIBLE TO MOST USERS
- FORMAT A INPUT DATA FREQUENTLY NOT TRACEABLE
- SOME PRICES IN COST ACCOUNT CATALOG OUTDATED
- ENVIRONMENTAL CONTROL ALGORITHMS NEED IMPROVEMENT

ACTION

- PUBLISH DOCUMENT WITH DETAILED VALIDATION AND EXPERIENCE
- NEW FORMAT A SHOULD LEAD TO BETTER INPUT DATA DERIVATION AND TRACEABILITY
- COST ACCOUNT CATALOG BEING UPDATED FOR RELEASE 4
- MAJOR EFFORT TO IMPROVE EFFLUENT CONTROL ALGORITHMS AND UPDATE CONTROL EQUIPMENT AND PROCESS COSTS

SAMICS CATALOGUE CHANGES

JET PROPULSION LABORATORY

R.W. Aster

PURPOSES:

- IMPROVE ESTIMATES OF ENVIRONMENTAL EFFLUENT COSTS
- UPDATE INFLATION ESTIMATES
- EXPAND, UPDATE, AND BETTER SPECIFY THE COMMODITIES LIST
- INCORPORATE SOME SUGGESTIONS MADE AT THE LAST LSA PIM

STATUS AND SCHEDULE:

INITIAL WORK ON ENVIRONMENTAL EFFLUENTS IS NOW COMPLETED. A REVIEW ALSO HAS BEEN COMPLETED

NEW INFLATION RATES HAVE BEEN PROJECTED. A JPL REVIEW OF THESE AND OF OTHER SAMICS FINANCIAL PARAMETERS IS SCHEDULED FOR NEXT WEEK

AN UPDATED COMMODITIES LIST HAS BEEN ASSEMBLED OVER THE LAST SEVERAL MONTHS (THIS IS AN ONGOING TASK). CONTRACTOR INPUTS HAVE BEEN MOST HELPFUL

DATA ENTRY WILL BEGIN IN 2 WEEKS. COST IMPACTS WILL BE INVESTIGATED BEFORE THE NEW CATALOG AND RELEASE 4 OF SAMIS ARE MADE AVAILABLE FOR GENERAL USE, PROBABLY IN AUGUST

ENERGY PAYBACK OF FLAT-PLATE PV MODULES AND ARRAYS

JET PROPULSION LABORATORY

R.W. Aster

Energy Content of Flat-Plate PV Modules

ENERGY CONTENT OF PV MODULES INCLUDES THE ENERGY CONTENT OF ALL MATERIALS AND SUPPLIES PLUS DIRECT AND INDIRECT ENERGY REQUIREMENTS OF THE PV FACTORY

THE MAIN CONTRIBUTORS TO PV ENERGY CONTENT HAVE BEEN:

- SILICON MATERIAL
- ENERGY REQUIRED TO GROW AND SAW INGOTS
- ENCAPSULATION MATERIALS

PV TECHNOLOGY IS CHANGING RAPIDLY:

- NEW SILICON PURIFICATION PROCESSES (1/3 LESS ENERGY CONTENT)
- SILICON REQUIREMENTS ARE BEING REDUCED
- ENCAPSULANT MATERIALS ARE BEING OPTIMIZED

THIS SUBJECT IS IMPORTANT BECAUSE OF NUMEROUS MISLEADING REPORTS IN RECENT POPULAR AND TECHNICAL JOURNALS

THE SCOPE OF THIS PRESENTATION INCLUDES THE EXPECTED EVOLUTION OF PV MODULES FROM 1976 TECHNOLOGY TO POTENTIAL GRID-CONNECTED TECHNOLOGY. FURTHERMORE, THE ENERGY CONTENT OF AN ARRAY STRUCTURE, INSTALLATION, AND OTHER ELEMENTS OF BOS ARE CALCULATED FOR A LARGE GROUND-MOUNTED ARRAY

1976 PV Technology Module Energy Content (kWh/kW_p)

	TERRESTRIAL	SPACE
SILICON	11,250	22,500
DIRECT AND INDIRECT PROCESS ENERGY	2,300	5,000
ENCAPSULANTS	1,500	1,500
TOTALS	15,050	29,000

ENERGY PAYBACK TIMES RANGE FROM 6 TO 11 yrs FOR TERRESTRIAL PV, 11 TO 21 yrs FOR SPACE CELLS, BASED ON INSOLATION RANGING FROM 1400 TO 2500 kWh/kW_p

Future (Near-Term) PV Module Energy Content (kWh/kW_p)

	kWh/kW_p	BASED ON
SILICON	5,400	12 kg SILICON /kWp
DIRECT AND INDIRECT PROCESS ENERGY	1,400	\$2.70/ W FACTORY PROCESSES, MATERIALS
ENCAPSULANTS	700	3/16 in. LOW-IRON GLASS EVA, TEDLAR, 9.6% MODULE
TOTAL	7,500	

ENERGY PAYBACK TIMES WILL RANGE FROM 3 TO 5.4 yrs

Potential (Late 1980s) PV Module/Energy Content

	kWh/kW_p	BASED ON
SILICON	480	DENDRITIC WEB, 3.2 kg/kW_p NEW Si PROCESSES
DIRECT AND INDIRECT PROCESS ENERGY	460	LESS Si MELTED, NO SAWING
ENCAPSULANTS	560	13.3% MODULE
TOTAL	1500	

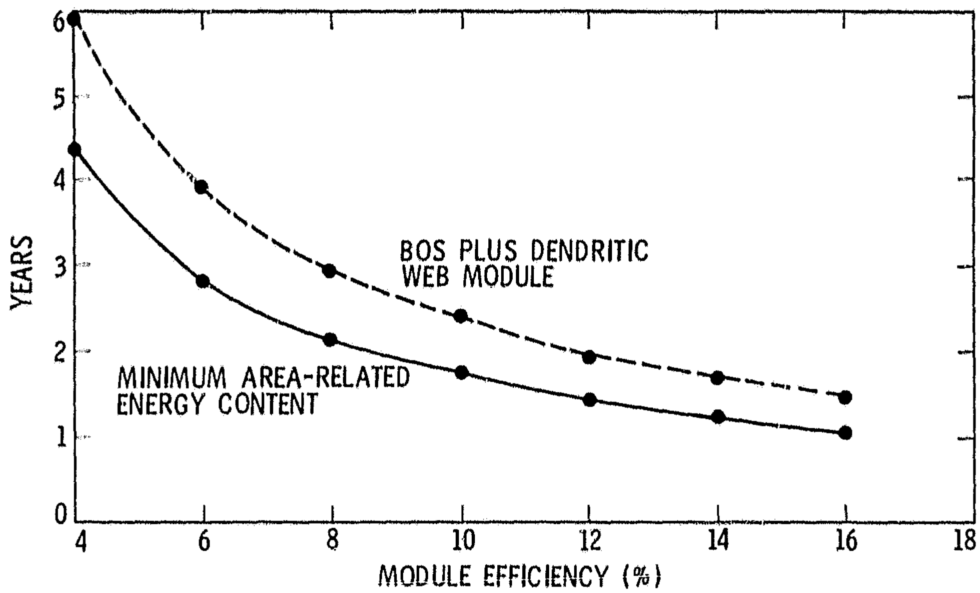
ENERGY PAYBACK TIMES FOR THE MODULE (NO BOS) RANGE FROM 0.6 TO 1.1 yrs

Potential BOS Energy Content

	kWh/kW_p	BASED ON
STRUCTURE MATERIALS		
STEEL	1370	LSA ENGINEERING ARRAY STRUCTURE DESIGN 2 kW_p/ STRUCTURE 13.3% MODULES
WOOD	457	
HARDWARE	43	
TRENCHES, SITE PREP	70	2 TRENCHES, 2 h WITH HEAVY EQUIPMENT
INSTALLATION, CABLING, OTHER	140	CENTRAL STATION, SUBSTATION NOT INCLUDED
TOTAL	2080	

ENERGY PAYBACK TIMES FOR THE BOS (NO MODULE) RANGE FROM 0.8 TO 1.5 yrs FOR CENTRAL STATIONS

Energy Payback as a Function of Module Efficiency



BASED ON 2000 kWh/kW_p/yr INSOLATION. MINIMUM AREA-RELATED ENERGY CONTENT BASED ON BOS PLUS GLASS ONLY

Conclusions

ENERGY PAYBACK TIMES ARE CHANGING DUE TO FUNDAMENTAL CHANGES IN PV TECHNOLOGY

SINGLE-CRYSTAL-SILICON FLAT-PLATE PV SYSTEMS CAN HAVE AN ENERGY PAYBACK TIME OF 1.4 TO 2.6 yrs, WHICH IS MUCH LESS THAN EXPECTED SYSTEM LIFETIME

LOW EFFICIENCY PV CONCEPTS (e.g., SOME THIN FILMS) WILL REQUIRE LONGER ENERGY PAYBACK TIMES DUE TO AREA-RELATED ENERGY REQUIREMENTS

SPINOFF BENEFITS FROM LSA PROJECT R&D

JET PROPULSION LABORATORY

R.W. Aster

THESIS

THE LSA PROJECT HAS CONDUCTED R&D TO RESOLVE PROBLEMS OF LOW-COST PV MANUFACTURING. THE TECHNOLOGY DEVELOPED SO FAR, AND TECHNOLOGY THAT MAY BE DEVELOPED, CAN ALSO (IN SOME CASES) PROVIDE SIGNIFICANT SPINOFF BENEFITS TO SEMICONDUCTOR AND OTHER TECHNOLOGIES.

ANALYSIS PROBLEM

ESTIMATE THE NET SPINOFF BENEFITS OF LSA PROJECT PV R&D. "NET SPINOFF BENEFITS" MEANS ECONOMIC BENEFIT OF TECHNOLOGY ADVANCES ABOVE AND BEYOND WHAT COULD REASONABLY HAVE BEEN ACCOMPLISHED IN THE WORLD WITHOUT AN LSA PROJECT.

Why Would Any Net Benefits Occur?

PV R&D HAS OCCURRED IN HIGH-RISK AREAS

- SILICON MATERIAL R&D
- NEW INGOT SAWING AND RIBBON TECHNOLOGIES
- NEW MANUFACTURING PROCESSES

PAYBACK FROM PV R&D SPINOFFS (IF SUCCESSFUL) OCCURS MANY YEARS AFTER THE R&D EXPENDITURE, DISCOURAGING INVESTMENT IN PRIVATE R&D, PARTICULARLY IN SMALL FIRMS.

PAYBACK FROM AN R&D PROJECT MAY BE SMALL FOR INDIVIDUAL FIRMS, BUT LARGE FOR AN INDUSTRY.

SOME PV R&D SPINOFFS BENEFIT THE SEMICONDUCTOR INDUSTRY. SEMICONDUCTOR R&D EMPHASIZES DEVICE QUALITY AND MINIATURIZATION. PV R&D EMPHASIZES MATERIAL COSTS, YIELDS, AND AUTOMATION. THESE OBJECTIVES TEND TO BE COMPLEMENTARY RATHER THAN DUPLICATIVE.

Some Potential Spinoffs

VERY LIKELY

- SEMICONDUCTOR-GRADE POLYCRYSTALLINE SILICON
- LOWER-COST SEMICONDUCTOR INGOTS
- LOWER-COST WAFERING
- ION IMPLANT COST REDUCTION (AUTOMATION)
- SILANE, LOW-COST/HIGH-PURITY SEMICONDUCTOR-GRADE
- NaOh ETCH, RATHER THAN ACID ETCHING OF WAFERS

POSSIBLE

- MIDFILM METALLIZATION OF PRINTED CIRCUITS
- EVA SUBSTITUTED FOR OTHER MATERIALS
- SILICON AND SILANE USED IN NEW APPLICATIONS

LESS LIKELY OR HARDER TO QUANTIFY

- GLASS THICKNESS SIZING ALGORITHM
- ION PLATING FOR CORROSION PROTECTION
- LOW-COST STRUCTURES

Semiconductor Polycrystalline Silicon

HIGH-RISK R&D (< 20% SUCCESS RATE).

UNANTICIPATED (SOLAR-GRADE SILICON WAS EXPECTED).

A HIGH ESTIMATE OF NET BENEFITS IS BASED ON INDUSTRY (IN THE ABSENCE OF PV R&D) CONTINUING TO RELY ON SEIMENS PROCESS TECHNOLOGY, WITH THAT TECHNOLOGY IMPROVING OVER TIME.

A LOW ESTIMATE OF NET BENEFITS ASSUMES THAT INDUSTRY ACHIEVES A BREAKTHROUGH (IN THE ABSENCE OF PV R&D) THAT WOULD HAVE ALLOWED IT TO MEET PROJECT GOALS ($14/kg) BY 1991, ANYWAY.

High and Low Estimates of Silicon Benefits

YEAR	REQUIRED REVENUE PROJECTION 1980 $/kg	LOW ESTIMATE		HIGH ESTIMATE	
		BREAKTHROUGH 1980 $/kg	BENEFITS (MILLIONS, $)	SEIMENS 1980 $/kg	BENEFITS (MILLIONS, $)
1982	70	80	31	80	31
1983	65	75	34	75	34
1984	60	70	38	70	38
1985	50	65	63	65	63
1986	40	60	94	60	94
1987	14	55	206	55	206
1988	14	55	227	55	227
1989	14	55	249	55	249
1990	14	50	240	50	240
1991	14	14	0	50	252
1992	14	14	0	50	265

A Summary of Low and High Estimates

SPINOFF	NET PRESENT VALUES (MILLIONS, $)	
	LOW ESTIMATE	HIGH ESTIMATE
SILICON	709	1270
INGOT GROWTH	244	1670
WAFERING	101	282
ION IMPLANT	0	412
SILANE	66	200
TOTALS	1, 120	3, 834

NET PRESENT VALUES ARE BASED ON 7% REAL DISCOUNTING.
NOT EVERY SPINOFF HAS BEEN ANALYSED YET.

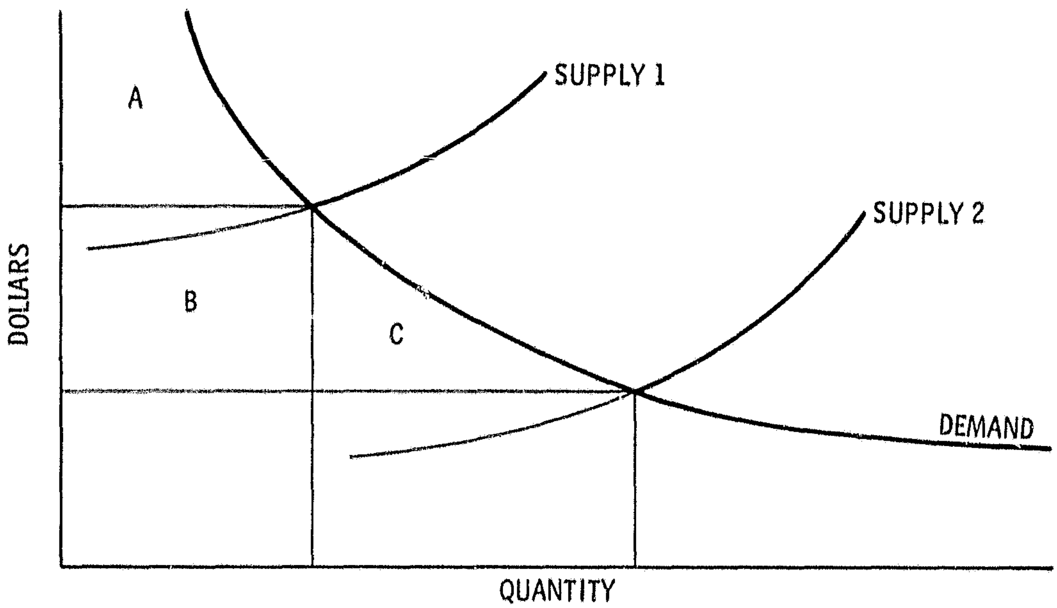
Concluding Comments

THESE SPINOFFS WERE NOT ORIGINALLY ANTICIPATED, AND FURTHER INVESTIGATION IS REQUIRED TO OBTAIN MORE PRECISE ESTIMATES.

THEIR MAGNITUDE IS LARGE COMPARED TO PV R&D EXPENDITURES TO DATE, BUT LESS THAN 1% OF THE SIZE OF THE SEMICONDUCTOR INDUSTRY ($300 TO $500 BILLION IN REVENUE BETWEEN 1980 AND 1995).

SPINOFFS FROM FUTURE PV R&D ARE POSSIBLE, BUT ESTIMATES CANNOT BE MADE DUE IN PART TO UNCERTAINTY ABOUT FUTURE PROGRAM FUNDING AND EMPHASIS.

Consumer Surplus — Producer Surplus Benefits



ENVIRONMENTAL EFFLUENT COSTS

JET PROPULSION LABORATORY

R. Gershman

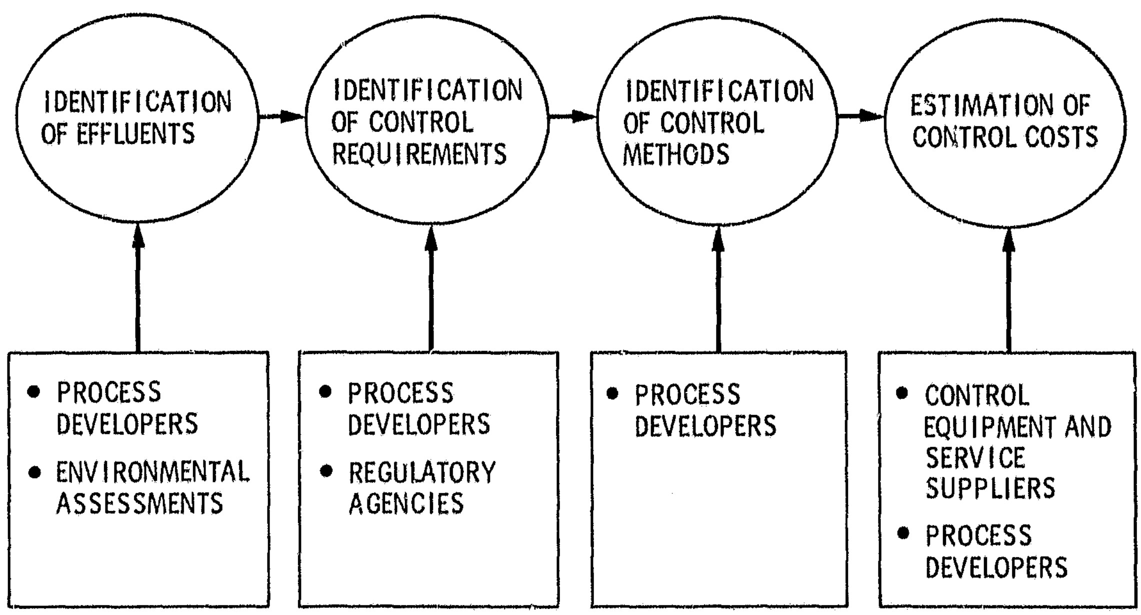
OBJECTIVE

- IMPROVE COST ESTIMATES FOR PROCESS WASTE DISPOSAL AND POLLUTION CONTROL
  - COVER ALL EFFLUENTS WITH POTENTIALLY SIGNIFICANT COSTS
  - ALL REQUIREMENTS TRIGGERED BY SPECIFICATION OF BY-PRODUCTS ON FORMAT-As

OUTLINE

- COST ESTIMATION APPROACH
- DESCRIPTION OF MATERIAL ADDED TO COST CATALOG
- REQUEST FOR FEEDBACK

Approach to Cost Estimation



Notes on Approach to Cost Estimation

- EFFLUENT CATEGORIES BASED ON CALIFORNIA REQUIREMENTS
- VARIATION OF CONTROL METHOD WITH SCALE INCLUDED
- RELIANCE ON JUDGMENT OF PROCESS DESIGNERS
  - UNCERTAINTY OF REGULATIONS
  - DEPENDENCE ON PROCESS DETAILS

Cost Catalog Effluent Entries

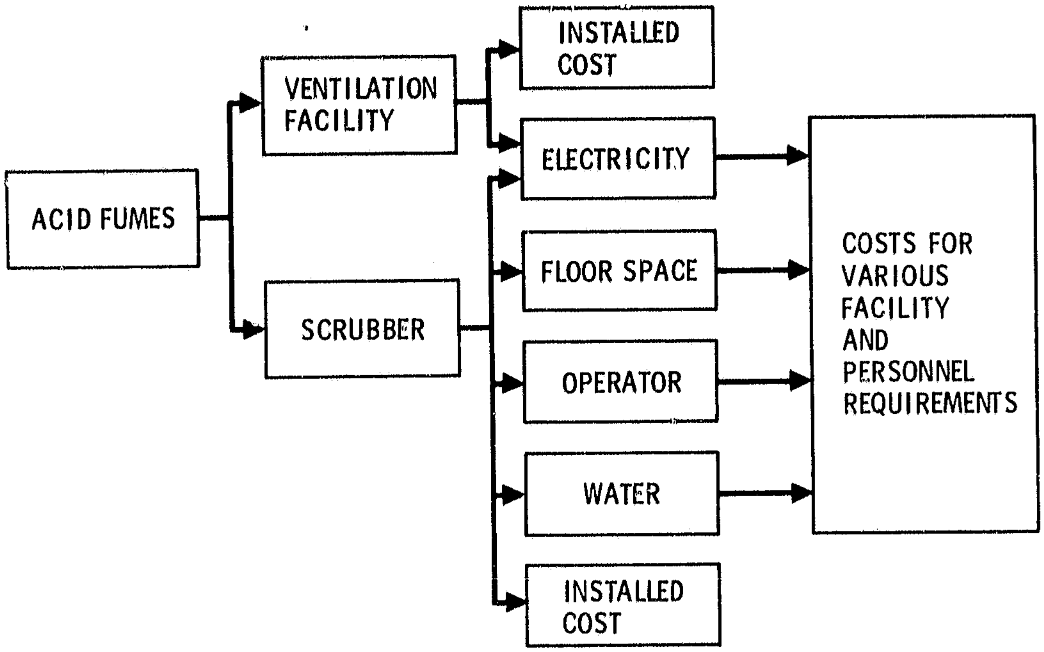
EFFLUENT		CONTROL METHOD
LIQUIDS	WASTE WATER	NONE OR CLARIFIER
	ACIDS OR ALKALIS	NEUTRALIZATION OR NEUTRALIZATION WITH CHEMICAL TREATMENT
	HAZARDOUS OR EXTREMELY HAZARDOUS	LANDFILL
OIL MIST		MIST COLLECTOR
SLURRIES OR SLUDGES OR SOLIDS	NON-HAZARDOUS OR HAZARDOUS OR EXTREMELY HAZARDOUS	LANDFILL
SOLVENTS	CHLORINATED	RECYCLE BY VENDOR OR IN-PLANT
	COMBUSTIBLE	RECYCLE BY VENDOR OR CATALYTIC INCINERATION OR THERMAL INCINERATION

EFFLUENT		CONTROL METHOD
FUMES		VENTILATION
	ACID OR ALKALI	VENTILATION AND SCRUBBER
	ORGANIC	VENTILATION AND ADSORBER OR CATALYTIC BURNER OR THERMAL BURNER
	HAZARDOUS OR EXTREMELY HAZARDOUS	VENTILATION, SCRUBBER, LANDFILL
	HYDROGEN FLOURIDE	VENTILATION, SCRUBBER
	CYANIDES	VENTILATION, SCRUBBER
DUST		VENTILATION AND FILTER OR SCRUBBER
	HAZARDOUS OR EXTREMELY HAZARDOUS	VENTILATION, FILTER, LANDFILL

Cost Catalog Entries Not Triggered By By-Products

- MONITORING
    - HAZARDOUS GASES
    - COMBUSTIBLE GASES
    - ARSINE/PHOSPHINE
- PERMITS AND ENVIRONMENTAL COORDINATION

Requirements Triggered by By-Product Entry



Request for Feedback

- OMISSIONS
- ACCURACY
- DIFFICULTIES IN APPLICATION TO PARTICULAR PROCESSES

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Summary of the 18th PIM

As a user of modules for assembly in photovoltaic systems, Ron Matlin of TriSolar Corp. had comments and suggestions:

High price of modules is still the major barrier to widespread use of photovoltaics.

Cost of installation of today's small modules into systems of 1 kW or larger is significant.

Shift as much work as possible from field to factory; e.g., from installation viewpoint, ideal module size is 4 ft x 6 ft for a 3 kW or larger system.

System power mismatch losses can be reduced by as much as 3 to 5% by amount of paralleling in a module.

The viewpoints and requirements of the Arizona Public Service Utility for future use of photovoltaics were presented by Merwyn Brown. Photovoltaics can be utilized effectively, but the extent and manner of incorporation varies with the specific utility and its loading and other generating characteristics.

Nearly all of the equipment for the Union Carbide Corp. 100 MT/yr silane-to-silicon experimental process system development unit (EPSDU) has been delivered to the construction site; mechanical and electrical installation are scheduled next, before checkout and operation. Preliminary fluidized-bed process development unit (PDU) tests were successfully run using silane concentrations of 10% to 21% in hydrogen (minimum economic design point is 10%). Freeflowing silicon shot was obtained in some initial tests of the silicon-powder-melting consolidation equipment.

The Hemlock Semiconductor Corp. PDU for investigating redistribution of trichlorosilane (TCS) to dichlorisilane (DCS) was completed, integrated with an intermediate-scale reactor, and operated successfully. Operation of the intermediate-scale reactor on cylinder-fed DCS confirmed silicon deposition rates required to meet the process goal.

In the investigation of the effects of impurities and processing on silicon solar-cell performance, Westinghouse confirmed that, at least for vanadium, molybdenum, and chromium, the threshold impurity concentration for breakdown of a smooth crystal-liquid interface is two to 10 times smaller for polycrystalline than for single-crystal ingots. Extensions of the experimentally supported impurity performance model to high-efficiency devices indicate that impurity tolerance is less in high-efficiency devices than in conventional n^+p devices and that impurity sensitivity can be reduced by using thinner high-efficiency cells.

A 2-in.-dia fluidized-bed reactor (FBR) was successfully operated at JPL using very high silane concentrations in hydrogen, indicating an attractive potential usefulness of the FBR.

The advanced-Cz ESGU initial operation resulted in the growth of five 15-cm-dia ingots (total weight 150 kg) from one crucible, but using manual control (throughput rates and single crystal yield require improvement).

Semix Inc. has demonstrated that technical readiness for the \$2.80 W_p goal has been met for its ubiquitous crystallization process (UCP) in module manufacturing.

Progress continues on the critical elements of the edge-defined film-fed growth (EFG) and web ribbon technologies.

Material suppliers (Du Pont Corp., Dow Corning Corp., 3M Corp., and others) recently made material, new or tailored for photovoltaics, available in commercial quantities for the photovoltaic industry. These materials were made to Low-Cost Solar Array Project (LSA) specifications but were not funded by LSA or the Department of Energy (DOE). LSA will perform life testing of these materials, which were on display. LSA encourages direct photovoltaic industry and material suppliers interaction.

Specific techniques for detecting and assessing corrosion mechanisms on solar cells and in modules have been developed.

Analytical models of chemical kinetic degradation rates in EVA have been developed. Accelerated experimental verification methods are being developed.

Spire's pulsed-electron-beam annealing (PEBA) machine successfully annealed 4-in.-dia wafers.

Bernd Ross Associates has metallized cells using a copper-based thick-film ink that incorporates a fluorocarbon as a fluxing agent.

A Westinghouse ultrasonically bonded aluminum-to-copper sample encapsulated in EVA withstood 30 days of immersion in water.

The Clemson University accelerated solar-cell stress study of 12 types of silicon solar cells was summarized. The major differences noted in cell reliability characteristics are attributed to metallization technology differences; i.e., vacuum deposition, plating, screen printing, and soldering. Cells with copper-plated metal contacts were the least durable from a contact adhesion and mechanical stress viewpoint. There was no evidence of Cu diffusion into the silicon of the tested cells (Ni barrier worked well). Thus, it is important that metallization studies continue, especially on Cu, which can be the lowest-cost type of metallization. Three cell manufacturers offered to donate new cell types for the next round of testing at Clemson.

Module hot-spot and cell-interconnect fatigue nomographs have been devised.

PIM SUMMARY

TECHNOLOGY DEVELOPMENT AREA

Silicon Material Task

Union Carbide Corp.

- DEMONSTRATE EXPERIMENTAL OPERATION OF MG Si/SiH_4/Si PROCESS (CAPABLE OF <$14/KG PRODUCTION)

- EPSDU -

  CIVIL AND STRUCTURAL WORK COMPLETED -- NEARLY ALL EQUIPMENT DELIVERED TO SITE -- MOST MAJOR EQUIPMENT PIECES INSPECTED AND PLACED IN POSITION -- MECHANICAL INSTALLATION BID PACKAGES BEING EVALUATED -- MECHANICAL INSTALLATION DELAYED FROM END OF JUNE DUE TO FUNDING LIMITATIONS

- FLUIDIZED-BED PDU -

  TESTS SUCCESSFULLY COMPLETED WITH 10% TO 21% SILANE IN HYDROGEN (MINIMUM ECONOMIC DESIGN POINT IS 10%) -- PROGRAM STOPPED IN MID-JULY DUE TO FY '81 FUNDING RECISION

- Si POWDER MELTING/CONSOLIDATION -

  INITIAL TESTS WITH CHUNK Si COMPLETED -- FREE-FLOWING SHOT OBTAINED IN SOME TESTS

- TO BE DONE -

  REMAINDER EPSDU PROGRAM - MECHANICAL AND ELECTRICAL INSTALLATION, CHECK-OUT, ESTABLISH SILANE PURITY, EXPERIMENTAL INTEGRATED/STEADY STATE PROCESS OPERATION WITH FSR/SHOTTER PYROLYSIS UNIT, DEMONSTRATING Si PURITY, EXPERIMENTAL INTEGRATED/STEADY-STATE PROCESS OPERATION WITH FBR UNIT

MIT-Solarelectronics, Inc.

TWO-YEAR PROGRAM AT MIT COMPLETED -- STUDY OF HYDROCHLORINATION OF MG-SI AND STC TO TCS TO BE CONTINUED UNDER CONTRACT TO SOLARELECTRONICS WITH SAME PRINCIPAL INVESTIGATOR -- PROCESS PROVIDES TCS FOR BOTH UCC AND HEMLOCK PROCESSES AND POTENTIALLY FOR CONVENTIONAL (SIEMENS) PROCESS FOR SEMICONDUCTOR - GRADE SI -- IN MIT STUDY THE FUNDAMENTAL OPERATING PARAMETERS OF PROCESS WERE WELL CHARACTERIZED -- IN NEW CONTRACT FUNDAMENTAL PROCESS PARAMETERS WILL BE INVESTIGATED USING ENGINEERING -SCALE FBR

Hemlock Semiconductor Corp.

- OBJECTIVE -- DEMONSTRATE FEASIBILITY OF DCS - BASED CVD PROCESS FOR PRODUCTION OF LOW-COST, HIGH PURITY SI
- CONSTRUCTION OF PDU FOR INVESTIGATING REDISTRIBUTION OF TCS TO DCS COMPLETED
- HEAT SHIELD FOR INTERMEDIATE - SCALE SI DEPOSITION REACTOR MODIFIED TO CONTAIN BELL JAR FRAGMENTS IN CASE OF EXPLOSION OF DCS-HYDROGEN-AIR MIXTURE -- REACTOR WITH HEAT SHIELD SUCCESSFULLY PASSED SAFETY TEST
- INTERMEDIATE-SCALE REACTOR OPERATED SUCCESSFULLY ON CYLINDER-FED DCS -- DATA CONFIRM HIGH SI DEPOSITION RATES THAT ARE NEEDED TO MEET PROGRAM OBJECTIVES
- PDU INTEGRATED WITH INTERMEDIATE-SCALE REACTOR AND OPERATED SUCCESSFULLY
- TWO PROBLEMS ENCOUNTERED -- AMOUNT OF SI DEPOSITED ON REACTOR WALLS (2% OF TOTAL DEPOSIT) GREATER THAN DESIRED -- REACTOR POWER CONSUMPTION HIGHER THAN DESIRED
- TO BE DONE -

  COMPLETE EXPERIMENTAL PROGRAM WITH INTEGRATED PDU/INTERMEDIATE-SCALE REACTOR TO INVESTIGATE PROCESS PARAMETERS

Westinghouse R&D Center

OBJECTIVE -- DETERMINE EFFECTS OF IMPURITIES, PROCESSING, AND IMPURITY-PROCESS INTERACTIONS ON PROPERTIES OF Si AND SOLAR CELLS TO PERMIT DEFINITION OF IMPURITY EFFECTS ON SOLAR CELL PERFORMANCE AND TO ALLOW COST-PERFORMANCE TRADE-OFFS TO BE MADE

- PHASE IV EFFORT COMPLETED -
  - EVALUATION OF EXPERIMENTAL Si MATERIALS
  - INVESTIGATION OF IMPURITY EFFECTS IN POLYCRYSTALLINE DEVICES
  - IDENTIFICATION OF IMPURITY THRESHOLDS FOR HIGH-EFFICIENCY CELLS
  - ASSESSMENT OF PROCESS EFFECTS SUCH AS ION IMPLANTATION ON IMPURITY-DOPED DEVICES
  - IDENTIFICATION OF LONG-TERM IMPURITY EFFECTS
- THRESHOLD IMPURITY CONCENTRATION FOR BREAKDOWN OF SMOOTH CRYSTAL-LIQUID INTERFACE IS 2 TO 10 TIMES SMALLER FOR POLY-Si THAN FOR SINGLE-CRYSTAL Si

- IMPURITY TOLERANCE APPEARS LOWER IN HIGH-EFFICIENCY DEVICES THAN IN CONVENTIONAL n^+p DEVICES -- IMPURITY SENSITIVITY REDUCED IN THINNER HIGH-EFFICIENCY CELLS

- NO CONTINUATION -- BUDGET RESTRICTION

C.T. Sah Associates

- PURPOSE -- DEVELOP COMPUTER MODEL BASED ON FUNDAMENTAL PARAMETERS OF SOLAR CELLS AND APPLY IT TO DETERMINATION OF EFFECTS OF IMPURITIES AND DEFECTS IN Si ON SOLAR CELL PERFORMANCE

- EFFECT OF CELL THICKNESS ON PERFORMANCE OF Si SOLAR CELLS CONTAINING IMPURITY RECOMBINATION CENTERS WAS ANALYZED USING ZINC IMPURITY AS THE MODEL RECOMBINATION CENTER -- EFFICIENCY PEAKS AROUND CELL THICKNESS OF ABOUT 50μM BUT PEAK IS VERY BROAD (LESS THAN 0.1% VARIATION FROM 20 TO 70μM) IN BSF CELLS OF 17% EFFICIENCY -- OTHER FACTORS LIMITING PERFORMANCE OF THIN CELLS IDENTIFIED

TO BE DONE --

- EXPERIMENTAL AND THEORETICAL ANALYSIS OF RECOMBINATION RATE DATA TO MAKE ACCURATE PREDICTIONS OF MAXIMUM ALLOWABLE IMPURITY CONCENTRATIONS FOR GIVEN CELL EFFICIENCIES

JPL In-House Program

- PURPOSE -- OBTAIN (1) CHEMICAL AND CHEMICAL ENGINEERING DATA FOR HIGH POTENTIAL Si REACTORS AND (2) BASIC INFORMATION OF EFFECTS OF IMPURITIES ON Si MATERIAL AND SOLAR CELL CHARACTERISTICS
- TO PROVIDE BASIS FOR EXPERIMENTAL PROGRAM USING 6-INCH-DIA. FBR, TESTS WERE RUN IN 2-INCH DIA. FBR TO INVESTIGATE Si FINES FORMATION AND BED AGGLOMERATION -- TESTS CONDUCTED SUCCESSFULLY AT HIGH SILANE CONCENTRATION IN HYDROGEN (INCLUDING 100% SILANE) WITHOUT EXCESSIVE FINES FORMATION OR BED AGGLOMERATION -- RESULTS INDICATE POSSIBILITY OF ACHIEVING LOWER COST BY MEANS OF INCREASED THROUGHPUT SINCE FBR OPERATION WITH AS LOW AS 10% SILANE SHOWN TO BE ECONOMICALLY ATTRACTIVE
- MEASUREMENTS OF ENERGY LEVELS AND DENSITIES CAUSED BY IMPURITIES BEING MADE USING TSCAP
- ZEEMAN ATOMIC ABSORPTION SPECTROMETER BEING ADAPTED TO MEASUREMENTS OF SOME IMPURITIES IN PPBA RANGE

TO BE DONE --

- R&AD PROGRAM WITH 6" FBR
- CONTINUE FUNDAMENTAL IMPURITY MEASUREMENTS AND RELATE THEM TO PERFORMANCE CHARACTERISTICS

Large-Area Silicon Sheet Task

Status

INGOT TECHNOLOGY

GROWTH

- o 150 KG OF INGOTS HAVE BEEN GROWN FROM ONE CRUCIBLE IN THE ADVANCED Cz ESGU.
  FIVE 15 CM DIA INGOTS WERE GROWN UNDER MANUAL CONTROL.
  50% OF THE INGOTS WERE SINGLE CRYSTAL.
  AVERAGE THROUGHPUT RATE IS 1.6 KG/HR (GROWTH RATE AT 2.5 KG/HR).
- o SEMIX HAS DEMONSTRATED THAT TECHNOLOGY PROJECTIONS CAN BE MET FOR $2.80/WP GOAL.
  ADDITIONAL WORK IS BEING RESCOPED TO FOCUS ON CRITICAL TECHNOLOGY ELEMENTS REQUIRED TO DEMONSTRATE TECHNICAL FEASIBILITY OF $0.70/WP.
- o BEST SIMULTANEOUS ACHIEVEMENT FOR HEM IS SOLIDIFICATION OF 30 x 30 x 15 CM. (36 KG) INGOT IN 18.5 HOURS. TOTAL GROWTH CYCLE TIME IS 51.5 HOURS.

INGOT TECHNOLOGY

WAFERING

- o SILICON MATERIAL UTILIZATION GOALS HAVE BEEN DEMONSTRATED FOR 15 cm DIA. AND 10 x 10 cm INGOT WAFERING. (17 WAFERS/cm AND 25 WAFERS/cm RESPECTIVELY.) KERF LOSSES REMAIN HIGH AT >10 MILS.
- o WAFER THROUGHPUTS DEMONSTRATED ARE TYPICALLY 0.25 WAFER/MIN. (GOALS ARE 0.5 WAFER/MIN AND 1 WAFER/MIN FOR 15 cm DIA AND 10 x 10 cm INGOT RESPECTIVELY.)
- o POTENTIAL FOR SLURRY VEHICLE RECLAMATION HAS BEEN DEMONSTRATED FOR THE MBS PROCESS.

RIBBON TECHNOLOGY

- o WORK CONTINUES ON DEVELOPING MODELS FOR ACHIEVEMENT OF HIGH WEB DENDRITE RIBBON THROUGHPUT (HIGH GROWTH RATE OF WIDE RIBBON) WITH COMMENSURATE MATERIAL QUALITY (15% AMI CELLS).
  FABRICATION AND ASSEMBLY OF AN EXPERIMENTAL GROWTH UNIT TO VERIFY ABOVE IS UNDERWAY.
- o ONGOING EXPERIMENTS FOR THE EFG PROCESS CONTINUE TO TEST NEW DIE DESIGNS AND GROWTH ATMOSPHERE VARIATIONS FOR THROUGHPUT AND QUALITY IMPROVEMENT.
  THREE RIBBONS OF 10 cm WIDTH EACH HAVE BEEN GROWN AT 3.3 cm/min. SIMULTANEOUSLY FOR 47% OF A 7.5 HOUR GROWTH CYCLE.

Additional Work

INGOT TECHNOLOGY

ADVANCED Cz

- o IMPROVEMENT OF INGOT QUALITY
- o INCREASED THROUGHPUT
- o CRUCIBLE/MELT INTERACTION

UCP

- o IMPROVEMENT OF MATERIAL QUALITY FOR 15% AM1 CELLS
- o DEMONSTRATION OF HIGH SPEED WAFERING OF 10 x 15 cm INGOTS

HEM

- o IMPROVEMENT OF MATERIAL QUALITY FOR 15% AM1 CELLS (E.G., REDUCE DISLOCATIONS AND PRECIPITATES)
- o IMPROVE INGOT GROWTH YIELD

WAFERING

- o INCREASE WAFERING THROUGHPUT
- o REDUCE KERF LOSSES

RIBBON TECHNOLOGY

WEB DENDRITE	o	INCREASE HEAT DISSIPATION FOR HIGHER GROWTH SPEED.
	o	MELT PROFILE AND THERMAL STRESS ANALYSIS FOR WIDE WEB GROWTH.
EFG	o	GROWTH AMBIENT ATMOSPHERE STUDIES FOR IMPROVED MATERIAL QUALITY.
	o	GROWTH ZONE THERMAL MODELLING TO REDUCE RIBBON STRESS AND BUCKLING.

Encapsulation Task

Encapsulant Materials

- STATUS
  - o MATERIAL AND SYSTEM REQUIREMENTS IDENTIFIED FOR EACH FUNCTIONAL ELEMENT (COVERS, POTTANTS, PRIMERS, ADHESIVES, EDGES, ETC.) FOR OPTICAL, THERMAL, ELECTRICAL, STRUCTURAL, PROCESSING, COST, ETC.
  - o NEW OR TAILORED MATERIALS FORMULATED, TESTED AND TRANSFERRED TO PV INDUSTRY FOR FABRICATION AND PERFORMANCE EVALUATION.
  - o MATERIAL SUPPLY INDUSTRY (DUPONT, DOW CORNING, 3M, ETC.) RESPONDING TO LSA REQUIREMENTS WITH NEW PRODUCTS AND TECHNICAL ASSISTANCE DIRECTLY TO PV INDUSTRY. (NOT DOE FUNDED, SEE EXHIBITS)
  - o TECHNOLOGY TRANSFER INTERFACES ESTABLISHED:
    WITHIN LSA PROJECT
    BETWEEN LSA PROJECT AND PV INDUSTRY
    BETWEEN LSA PROJECT AND MATERIAL SUPPLIERS
    BETWEEN PV INDUSTRY AND MATERIAL SUPPLIERS (E.G., ARCO, DUPONT, ETC.)

- NEEDED WORK

  - THESE ARE NEW MATERIALS AND NEW INTERFACE COMBINATIONS THAT NEED EVALUATION AND CHARACTERIZATION TO DEFINE PROPERTIES, APPLICATION LIMITS, PERFORMANCE MARGINS AND PROCESS OPTIMIZATION. COMBINATION INDUSTRIAL AND DOE SUPPORT IS APPROPRIATE.

  - DEFINE, COMPILE, UPDATE AND PUBLISH ENCAPSULANT DESIGN GUIDE LINES, DESIGN ANALYSIS METHODS AND MATERIAL SELECTION CRITERIA AND STANDARDS, FOR INDUSTRIAL EVALUATION AND ADOPTION.

  - ASSESS ADVANCED (HIGH RISK) MATERIAL AND FABRICATION CONCEPTS THAT HAVE LONG-TERM HIGH PAY-OFF POTENTIAL. EVALUATE FOR IMPROVED ENVIRONMENTAL STABILITY, LOWER MODULE LIFE CYCLE ENERGY COST, APPLICATION TO ADVANCED SOLAR CELLS.

Encapsulation Durability and Module Life

- STATUS

  - SCREENING AND RANKING TESTS OF CURRENT CANDIDATE MATERIAL SYSTEMS INDICATE 20-YEAR OR GREATER LIFE POTENTIAL IN RECOMMENDED DESIGNS (GLASS, EVA, EMA, SILICONES, PMMA, TEDLAR, ETC.)

  - DEGRADATION MECHANISMS AND EXPECTED PROPERTY CHANGES DUE TO ENVIRONMENTAL AGING HAVE BEEN DEFINED AND MEASURED.

  - PROGRESS MADE IN EVALUATING AND IMPROVING LIFE TESTING METHODS AND IN INTERPRETING ACCELERATION EFFECTS.

  - CHEMICAL AND ANALYTICAL COMPUTER MODEL OF EVA DEGRADATION RATE DEVELOPED AND BEING EXPERIMENTALLY VALIDATED.

PIM SUMMARY

- NEEDED WORK

  - ANSWER THE QUESTIONS
    HOW LONG WILL THE MODULE LAST?
    WHAT WILL BE THE PROBABLE WEAR-OUT FAILURE MODE?
    WHAT IS THE WEAK (LIFE-LIMITING) LINK IN THE DESIGN?
    WHAT CAN BE DONE TO INCREASE LIFE (REDUCE LIFE-CYCLE ENERGY COST)?

  - DEVELOP A SPECIFIC SET OF DESIGN ANALYSES AND COMPONENT TESTS FOR THE ASSESSMENT OF MODULE LIFE. (PARTIALLY ACCOMPLISHED)

  - UNDERSTAND AND BE ABLE TO DETECT AND CONTROL CORROSION MECHANISMS IN MODULE INTERNAL CIRCUIT ELEMENTS.

  - DETERMINE AND SPECIFY PHOTOTHERMAL STABILITY LIMITS OF ENCAPSULANTS UNDER ALL MODULE OPERATIONAL CONDITIONS.

  - DEFINE CRITICAL ENCAPSULANT INTERFACE STABILITY CRITERIA AS AFFECTED BY DISSIMILAR MATERIALS, BONDING TECHNIQUES AND OPERATIONAL STRESSES.

PROCESS DEVELOPMENT AREA

MEPSDU Status

- CONTRACTS RESCHEDULED; REDUCED FUNDING RATE
- PRELIMINARY DESIGN REVIEWS COMPLETED WITH MODIFIED DESIGN
- SOLAREX ESTABLISHED SUBCONTRACT FOR AUTOMATED SOLDERING MACHINE
- PROCESS DEVELOPMENT AREA LABORATORY BEGINNING TO PROCESS MEPSDU SILICON SHEET MATERIALS

Metallization

- CU THICK FILM SYSTEM REQUIRES SIMULTANEOUS MECHANICAL AND ELECTRICAL DEMONSTRATION
  - CU-PB-CX FY PASTE ADHERES AFTER H_2O BOIL TEST
  - NONOPTIMUM CU CELLS EQUIVALENT TO 10% η
- NI SILICIDE FORMATION APPEARS TO BE CRYSTAL ORIENTATION SENSITIVE
- PHOTOWATT WORKING ON NI PASTE FIRED THROUGH A/R COATING
- MIDFILM® PROCESS HAS CAPABILITY OF PUTTING BASE METALS ON IRREGULAR SURFACES
- COPPER PENETRATES 400 Å NI AFTER 15 MINUTES AT 300°C (WESTINGHOUSE)

Junction Formation

- SPIRE BEGINNING DESIGN OF NON-MASS ANALYZED ION IMPLANTATION
- PULSED ELECTRON BEAM ANNEALING (PEBA) MACHINE SUCCESSFULLY ANNEALED FOUR INCH DIAMETER WAFERS
- $POCl_3$ DIFFUSION WITH EPI ON UPGRADED METALURGICAL GRADE SILICON
- SOLAREX SPRAY-ON DOPANT APPEARS SUCCESSFUL

Surface Preparation

- MOTOROLA SHOWED SMALL BENEFIT FROM TEXTURING POLYCRYSTALLINE SILICON
- RCA EPI CELLS INFLUENCED BY SAWING SURFACE DAMAGE
- ITO A/R COATING REDUCES SERIES RESISTANCE

Assembly

- TRACOR MBA PROGRAMMABLE ROBOT FOR ENCAPSULATION AND EDGE SEALING AT DEMONSTRATION STAGE
- JPL IN-HOUSE WORKING TO INTRODUCE SOPHISTICATED SENSING TECHNIQUES
- WESTINGHOUSE ULTRASONIC BONDED Al TO Cu SAMPLE EVA LAMINATED WITHSTOOD 30 DAY H_2O IMMERSION

PIM SUMMARY

ENGINEERING AREA

MODULE RESEARCH

- o SOLAR CELL RELIABILITY (CLEMSON)
- o INTERCONNECT FATIGUE
- o HOT-SPOT HEATING THERMAL ANALYSIS
- o INTERNATIONAL ENVIRONMENTAL TESTS

ARRAY RESEARCH

- o INTEGRATED RESIDENTIAL ARRAYS (GE & AIA/RC)
- o ELECTRICAL SAFETY SYSTEM DEVELOPMENT (UL)
- o CLEANING STUDY

Activities Not Presented

MODULE RESEARCH

- o ELECTRICAL INSULATION BREAKDOWN
- o ENCAPSULANT SOILING
- o LONG-TERM HUMIDITY TESTING (WYLIE)
- o MODULE RELIABILITY STUDY (IITRI)
- o WIND COOLING (NOCT) ANALYSIS
- o MODULE ACCELERATED WEATHERING (DSET)

ARRAY RESEARCH

- o BUILDING CODE REVIEW (BHKRA)
- o RESIDENTIAL FIRE TESTING (UL)
- o GROUND-MOUNTED STRUCTURES
- o WIND LOADING ANALYSIS (BOEING)
- o POWER CONDITIONER INTERFACE REQUIREMENTS